LIGHTWEIGHT CONCRETE FROM RICE HUSK ASH

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By
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To

My Mother

CERTIFICATE

This is to certify that this work entitled, "LIGHTWEIGHT CONCRETE FROM RICE HUSK ASH" by Suresh Chand Jain has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Rice husk ash is a waste product of paddy and is available in vast quantities in India specially at mill sites. The disposal of ash is a problem. Rice husk ash is rich in silica and can be put to many uses. For example the amorphous nature of silica in rice husk ash has been exploited to get a cementitious material 'ASHMOH' by grinding it with lime. This pozzolanic cement has compressive strength values comparable to that of portland cement.

Rice husk ash is a good lightweight aggregate filler. In the present work a spectrum of lightweight concretes were made using rice husk ash, Ashmoh and sand in different proportions. Higher Ashmoh and sand levels gave higher compressive strength values but even at the higher rice husk ash levels the low compressive strength values of concretes could be upgraded by adding portland cement.

Steam-curing at 1 atm pressure was found and used as an alternative to 28 days water curing. Properties of steam-cured lightweight concrete were comparable or better than those of the water cured one.

Various additives had a pronounced effect on the compressive strength values of lightweight concrete. Calcium chloride (maximum upto 2.5 per cent of the weight of total cement) gave the best results.

Compressive strength, water absorption and shrinkage of the concretes made compared well with those of other commercial lightweight concretes.

Large amounts of rice husk ash could be used as building material in the form of Ashmoh cement or in the form of lightweight aggregate filler to make structural or insulative lightweight concretes.

CHAPTER - 1

INTRODUCTION

Lightweight concrete is a material which has been made lighter by one means or another than the conventional concrete, the very familiar product made from cement, sand and gravel which has been for so long a major building material. To make the description more quantitative, we say that lightweight concrete is a concrete with a dry bulk density of not more than 100-120 lb per cu ft (1600-1920 kg/m^3) which is significantly lighter than the dry bulk density of conventional concrete, 150 lb per cu ft (2400 kg/m^3) (1).

1.1 Lightweight Concrete:

It is of two types:

(i) Structural lightweight concrete (SLWC)

(ii) Insulating lightweight concrete (ILWC)

1.1.1 Structural Lightweight Concrete:

Structural lightweight concrete is used in practically every application of normal-weight concrete where a reduction in deadweight leads to significant savings in the cost of the structure. The chief reason for the remarkable success of lightweight concrete lies in the fact that it can attain high strength in combination with a relatively low bulk density and many other favourable properties.

(a) <u>Bulk density and strength</u>: Structural lightweight concrete lies in the bulk density range 85-120 lb per cu ft (1360-1920 kg/m^3) and is capable of exhibiting compressive strengths from 2500 psi to more than 6000 psi (176 kg/cm^2- 422 kg/cm^2). This range can be suitably subdivided into several closely defined bulk density groups so as to provide distinctive identification of structural lightweight concrete on the basis of bulk density. Concrete based on the use of artificial lightweight aggregates such as expanded clay or shale, sintered fly ash etc. and autoclaved concrete are the only types of lightweight concrete at present that can be used for the construction of load-bearing components. Current research is directed at obtaining aggregates with greater strength, without increasing their weight and also making them less hygroscopic. Such lightweight aggregates will be required in larger quantities in future as natural heavy aggregates are depleting fast.

In the bulk density range 1360-1920 kg/m^3, 28-day cube compressive strength of structural lightweight concrete is always above 200 kg/cm^2 and sometimes as high as 600 kg/cm^2. In general increase in strength runs parallel to the increase in bulk density of the concrete. Nevertheless, it is interesting to note that in a German product an average 28-day strength of 555 kg/cm^2 was obtained with a bulk density of only 1660 kg/m^3.

(b) Application: The application of structural lightweight concrete is governed by fundamentally the same properties as those relevant to ordinary concrete. With regard to some properties, however, there are a few significant differences apart from the higher cost of production of lightweight concrete, which are noteworthy.

(c) Other characteristics: The modulus of elasticity is seem to be much more dependent on the bulk density than on the strength of the concrete and ranges between 140,000 kg/cm^2- 250,000 kg/cm^2. The lower modulus of elasticity in comparison with that of ordinary concrete implies greater deformability; but this is not without certain advantages. For example, lightweight concrete exhibits better behaviour under earthquake conditions and less susceptibility to the effects of harmful forced deformations such as settlement of supports, thermal effects etc.

The shrinkage and creep of lightweight concrete are generally, but not always, a little greater; also the ratio of tensile to compressive strength is often somewhat lower than that of ordinary concrete. Lightweight concrete has an appreciably lower coefficient of thermal conductivity than ordinary concrete. Therefore, on exposure to fire the rise in temperature in the interior of the structural components will be less than in the case of ordinary concrete. As a result the rise in temperature of the reinforcement will also

be less, and this is a more favourable condition for fire protection. Hence the fire-resistance rating of structural lightweight concrete components, as determined in the fire test, is approximately one third higher than the fire-resistance rating of components made of ordinary concrete. One characteristic of lightweight concrete is its potential for rupture and indentation. This makes it easy to damage, but it also means that it can be nailed and treated much like wood.

(d) Economic Aspects/Advantages: Structural lightweight concrete offers economic advantages in many cases, since the higher cost of the artificial aggregate is often offset by the reduction in size and weight of the structural components and by the savings in reinforcing steel. Further, the reduction in deadweight enables savings in the cost of false-work and foundations. Transport and erection costs are also less. For equal overall structural weight, it is possible with lightweight concrete to construct taller buildings and longer spans. Hence the structural properties of the subsoil can be economically utilized, especially if it is of poor load bearing capacity. From these considerations it is evident that for assessing the economy of construction, it may be necessary not merely to take into account the cost of individual components and elements but also to examine the construction project as a whole. In this context, it is

important to consider not just aspects such as design, manufacture, transport, erection, or soil conditions, but also maintenance and operating costs (2,3).

1.1.2 Insulating Lightweight Concrete :

These concretes are specially designed to provide insulation against heat, cold, fire and sound. Structural properties are considered secondary to insulation value. Concrete with good thermal insulation properties resulting in lower air-conditioning and heating costs. Good insulation depends on keeping moisture out of the insulating concrete by appropriate construction techniques, including vapour barriers and venting channels for drying. Insulation from sound is controlled by weight, air-tightness, stiffness and edge fixing conditions. The aim is to reduce stiffness without reducing strength. Generally, increasing the weight of concrete will decrease the sound transmitted through it, but on the other hand the lightweight concretes are porous and, therefore, have the capability of absorbing sound. Normally, however, sound insulation is accomplished by higher-density concrete - 75 lb per cu ft (1200 kg/m^3) and up, whereas thermal insulating concretes are considered to be those below 50 lb per cu ft (800 kg/m^3) i.e. from 15 lb per cu ft (240 kg/m^3) to 50 lb per cu ft (800 kg/m^3).

1.2 Manufacturing Methods:

Lightweight concrete is not just one item; it is a spectrum of different concretes with a variety of characteristics and it fulfils a number of needs. Lightweight concrete can be made using various methods to get different products:

(i) No-fines concrete
(ii) Lightweight aggregate concrete
(iii) Aerated or foamed concrete
(iv) Autoclaved foamed concrete.

1.2.1 No-fines Concrete:

Inclusion of air in composition of concrete is achieved by omitting the finer sizes from the aggregate grading, thereby creating the so-called 'no-fines' concrete. Discussed in Chapter 2, see Figure 2.1(a).

1.2.2 Lightweight Aggregate Concrete:

Lightweight aggregate concrete is obtained by replacing the gravel or crushed rock aggregate by a hollow, cellular or porous aggregate which includes air in the mix (Figure 2.1(b)). This aggregate, namely lightweight aggregate is required to have a unit weight of 70 lb per cu ft (1120 kg/m^3) or less. "Spectrum" of concrete weights varying from a low of 15 lb per cu ft (240 kg/m^3) to a high of 120 lb per cu ft (1920 kg/m^3) can be obtained using various lightweight aggregate grades.

Spectrum of concrete weights made from various lightweight aggregates has, at the low end of the scale "super" lightweight aggregates: vermiculite and perlite. They are capable of producing a highly insulative concrete with compressive strengths ranging from 200 psi (14.061 kg/cm^2) to a maximum of 1000 psi (70.31 kg/cm^2). This concrete is used as an insulative roof fill over a structural system or as fireproofing. Vermiculite and perlite also find widespread use in making lightweight plaster. Next, group of lightweight concretes have strengths from 1000 psi (70.31 kg/cm^2) to 2000 psi (140.62 kg/cm^2) and unit weights between 50 lb per cu ft (800 kg/m^3) and 85 lb per cu ft (1360 kg/m^3). These are fill concretes that have some insulating value. Depending on the materials and the techniques of using them, these concretes may have properties of finishability or wearability and, at the high end of their range, they may be used in making small precase products. At the highest end of the scale is structural concrete varying in unit weight from 85 lb per cu ft (1360 kg/m^3) to 120 lb per cu ft (1920 kg/m^3) and capable of developing compressive strengths from 2500 psi (175.77 kg/cm^2) to more than 6000 psi (422 kg/cm^2).

1.2.3 Aerated or Foamed Concrete:

These are manufactured by creating gas bubbles in a cement slurry which when it sets leaves a sponge-like

cellular structure, and are termed 'aerated or foamed concrete' (Figure 2.1(c)). Aeration can be achieved by both physical and chemical means.

1.2.4 Autoclaved Foamed Concrete:

Calcareous and siliceous compounds are mixed foamed and autoclaved to get high-strength calcium-silicate foamed concretes.

1.3 Rice Husk Ash:

For making lightweight aggregate concrete in India, materials like vermiculite, perlite, pumice, scoria are either not available or are expensive. This leaves us with fly ash, expanded clay or shale and other wastes from industries. Fly ash in other countries is mainly used as a filler (up to 20% by wt.) in portland cement, without affecting the portland cement properties. Sintered fly ash and expanded (bloated) clay or shale involve high temperature (kiln) operations i.e. the processing cost of raw materials is higher.

Rice husk ash is a waste product of rice mills and is available in plenty in India. It has a very low bulk density (300-400 kg/m^3), porous structure and high surface area per unit weight. This material is rich in reactive silica. If the carbon content is kept less than

7% (usual restriction for pozzolanas) i.e. by proper burning, rice husk ash on grinding with slaked lime will yield cementitious material called Ashmoh which on hydration gives calcium silicate hydrates (4).

Thus, lightweight concrete from rice husk ash is a possibility as rice husk ash combines; (i) properties of lightweight micro aggregate in lightweight aggregate concrete manufacturing method, (ii) property - uniform homogeneous microporous structure in foamed concrete manufacturing method, and (iii) chemical composition and structure properties in autoclaved-foamed concrete manufacturing method.

1.4 Intentions of this Work:

The basic objective of this work was to study the feasibility of exploiting the huge amounts of rice husk ash and using it as a substitute building material. Lightweight concrete 'spectrum' was to be obtained from rice husk ash, sand and Ashmoh in different proportions. Strength characteristics of these concretes were to be obtained and checked if they met the lightweight concrete (both structural and insulative) requirements.

In brief, the investigation can be classified in the areas of:

(i) Lightweight concrete spectrum (1000-2000 kg/m^3)

(ii) Strength characteristics

- Tensile and compressive strengths
- Tensile to compressive strength ratio

(iii) Steam-curing time effect (saturated steam at one atm. i.e. 100°C)

(iv) Effect of additives, accelerators on compressive strength and setting time.

CHAPTER - 2

LITERATURE SURVEY

2.1 Lightweight Concrete:

The inclusion of air in the form of discrete entities in the structure of concrete makes it lighter. This can be achieved by (i) omitting the finer sizes from the aggregate grading, thereby creating the so-called 'no-fines' concrete, (ii) replacing the gravel or crushed rock aggregate by a hollow, cellular or porous type aggregate, (iii) by creating gas bubbles in a cement-filler slurry which when it sets leaves a sponge like cullular structure, termed aerated concrete, and (iv) by autoclaving a foamed mixture of lime and siliceous materials to get hydrothermally formed calcium silicates concrete. These are illustrated in Figure 2.1.

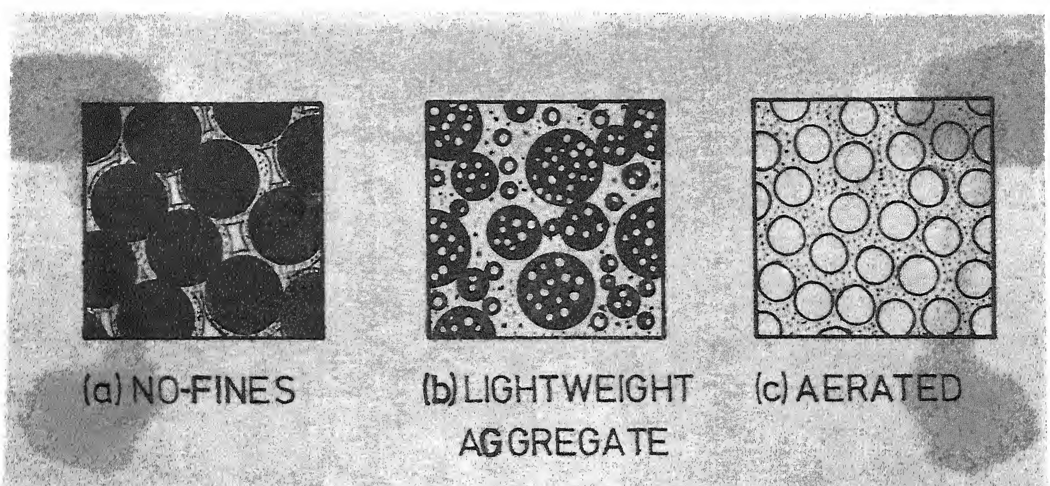


Figure 2.1 The three basic types of lightweight concrete

Concretes can be made which are combinations of the above types, for example, no-fines concrete employing lightweight aggregates, and aerated concrete containing cellular aggregate. Lightweight concrete can be categorized as in Table 2.1 (5).

All the concretes have a hydraulic cement matrix, hence many of the common properties of lightweight concrete, such as strength development, drying shrinkage, carbonation, and resistance to chemical attack are very much influenced by the properties of the cement bond itself.

<u>No-fines concrete</u> (5): The term <u>no-fines</u> concrete means a concrete composed of cement and a coarse (3/4 in (19.05 mm) - 3/8 in (9.525 mm)) aggregate only; the product has many uniformly sized voids but practically no capillary paths. It is used for load-bearing external and internal walls, non-load-bearing walls, infilling walls for framed structures, under-floor filling for solid floors and for roof screeds. The mix commonly used is 1:8 by volume for heavy aggregate and 1:6 for lighter clinker and the compressive strength varies; from 600 psi (42.2 kg/cm^2) to 2000 psi (140.6 kg/cm^2) at 28 days with bulk density of 1600 kg/m^3 - 1920 kg/m^3 for natural heavy aggregate, from 400 psi (28.1 kg/cm^2) to 1000 psi (70.3 kg/cm^2) with bulk density of 880 kg/m^3 - 1200 kg/m^3 for lightweight aggregate. In practice nowadays, no-fines concrete is made principally by weigh batching and

Table 2.1

Groups of lightweight concrete

No-fines concrete	Lightweight aggregate concrete	Aerated concrete: Chemical aerating	Aerated concrete: Foaming mixture	Autoclaved foamed concrete
(1) Gravel	(1) Clinker	(1) Aluminium and zinc powder method	(1) Preformed foam	(1) Calcium silicates concrete
(2) Crushed stone	(2) Foamed slag	(2) Hydrogen peroxide and bleaching powder method	(2) Air-entrained foam	
(3) Coarse clinker	(3) Expanded clay			
(4) Sintered pulverised-fuel ash	(4) Expanded slate			
(5) Expanded clay or shale	(5) Expanded shale			
(6) Expanded slate	(6) Sintered pulverised-fuel ash			
(7) Foamed slag	(7) Exfoliated vermiculite			
	(8) Expanded perlite			
	(9) Pumice			
	(10) Organic aggregates (plastic microspheres)			

the mix most commonly used is 1:8 by weight with a water/cement ratio of 0.40. The drying shrinkage of no-fines concrete is usually considerably less than that of all-in aggregate concrete made with the same materials. A wall of no-fines concrete made with heavy aggregate has thermal conductivity comparable with that of a solid brick wall of the same thickness. The modulus of elasticity of no-fines concrete tends to diminish with age. The sound insulation of party walls of no-fines concrete is no better than the solid brick walls of comparable thickness.

<u>Aerated concrete</u> (Chemical or foamed concrete) (1):

(a) <u>Chemical Aerating</u>: The chemical reaction method of foaming concrete using admixtures to generate gas bubbles is suitable for plant precasting. The admixtures may react chemically with each other or with certain compounds already present in the cementitious slurry. Aluminium or zinc powder is the most widely used agent in the commercial production of this type of concrete. It reacts with the alkalies in the cementitious mixture to generate hydrogen. According to the patent literature, hydrogen peroxide and bleaching powder may be used to generate oxygen, but they are not used commercially.

(b) <u>Foaming Mixture</u>:

<u>Mechanical Method</u>: Mechanical methods are easier to control than the chemical methods and are usually more economical. One method for producing low-density concrete

with little or no aggregate is the excess water method where a thin slurry of cementitious and aggregate materials is prepared with a quantity of water several times greater than the requirements for an equal volume of conventional concrete. The concrete is cured in high pressure steam (autoclaved) and allowed to dry. Finely divided air voids will form due to evaporation of the excess water. Foamed concretes made by this method are of low density and are often called "light-lime" concretes because lime is usually used as the cementitious ingredient.

In another method water and foaming agent are added first to the mixer to produce foam. Then the portland cement (and sand if needed) is added and the mixture is blended well.

Foam, mix-foam and prefoamed methods are other means to get aerated concrete.

Aerated concretes have compressive strengths ranging from 50 psi (3.515 kg/cm^2) to 3600 psi (253.1 kg/cm^2) and the bulk density range is usually from 15 lb per cu ft (240 kg/m^3) to 150 lb per cu ft (2400 kg/m^3). The foaming agents are water soluble surfactants that must be mixed in a special mixer. The high volume of air incorporated into the concrete mix results in a homogeneous cellular structure that is light in weight. These special concretes offer qualities of moisture resistance, good insulation, fire-resistance and non-corrosion of steel.

Autoclaved, Foamed Concrete: Calcium silicate concrete - Lime and silica can combine in any manner to yield calcium silicate compounds, hydrothermal synthesis gives hardening and strength development. Depending on the raw materials and process employed calcium silicate concrete has a wide range of properties and unit weight. Foaming is used to get light products followed by high pressure steam curing (autoclaving). The bulk density of an aerated autoclaved concrete block varies from 25 lb per cu ft (400 kg/m^3) to 55 lb per cu ft (880 kg/m^3) and strength from 300 psi (21.1 kg/cm^2) to 800 psi (56.2 kg/cm^2), whereas the bulk density of calcium silicate concrete varies from 105 lb per cu ft (1680 kg/m^3) to 130 lb per cu ft (2080 kg/m^3) and strength from 1500 psi (105.5 kg/cm^2) to 8000 psi (562.5 kg/cm^2).

Lightweight aggregate concrete was described in Chapter 1. Table 2.2 summarizes the above classification showing the density of aggregate, density of concrete, compressive strength and thermal conductivity for each concrete type.

2.2 Lightweight Aggregate:

Lightweight aggregate is any solid material in a concrete mix that weighs less than the usual sand, gravel, and crushed stone aggregate. According to specification, it has a bulk density of 70 lb per cu ft (1120 kg/m^3) or less.

Properties of different types of lightweight concretes p. 24 (5) and p. 486 (29)

Type of light-weight concrete	Aggregate	Bulk density of aggregate (kg/m^3)	Bulk density of concrete (kg/m^3)	Cube crushing strength at 28 days (kg/cm^2)	Thermal conductivity (kcal/ m.hr. °C)
(1) No-fines concrete	Natural aggregate	1360-1600	1600-1920	42.2-140.6	-
	Lightweight aggregate	480-1040	880-1200	28.1-70.3	-
(2) Lightweight aggregate concrete					
(A) Partially compacted	Expanded vermiculite	64-240	400-1120	4.92-35.2	0.093-0.248
	Expanded perlite	80-240	400-960	7.03-56.3	0.093-0.248
	Pumice	480-880	720-1120	14.06-38.6	0.186-0.248
	Foamed slag	480-960	960-1520	14.06-56.2	0.186-0.372
	Sintered pulverised-fuel ash	640-960	1120-1280	28.12-70.3	-
	Scoria	640-1040	960-1280	35.02-70.3	-
	Expanded clay or shale	560-1040	960-1200	56.2-84.4	0.285-0.397
	Clinker	720-1040	1040-1520	21.09-70.3	0.298-0.496
(B) Structural-densely compacted	Pumice	480-880	1120-1500	38.6-140.6	-
	Foamed slag	480-960	1680-2080	105.4-422.0	-
	Sintered pulverised-fuel ash	640-960	1360-1760	140.6-422.0	-
	Scoria	640-1040	1280-1840	70.3-281.0	-
	Expanded clay or shale	560-1040	1360-1840	140.6-422.0	-
	Clinker	720-1040	1520-1600	70.3-140.6	-

Continued...

Table 2.2 (continued)

Type of light-weight concrete	Aggregate	Bulk density of aggregate (kg/m^3)	Bulk density of concrete (kg/m^3)	Cube crushing strength at 28 days (kg/cm^2)	Thermal conductivity (kcal/m.hr.°C)
(3) Aerated concrete	-	-	400-800	14.06-49.2	0.0744-0.1735
(4) Autoclaved calcium silicate concrete					
-Aerated	-	-	400-880	21.1-56.2	-
-Dense	Natural aggregate	1360-1600	1680-2080	105.5-562.5	-

Lightweight aggregates can be classified into several categories (1).

(a) Natural aggregate

(b) By-product aggregate

(c) Processed aggregate

<u>Natural lightweight aggregates</u>: Pumice, scoria and diatomite are mined, crushed and washed to remove adhering impurities, the final product passes through a 3/8 in (9.525 mm) sieve but is retained in a 1/8 in (3.175 mm) sieve. Pumice is white or grey to yellow in colour and has a frothlike appearance. It is porous but firm and rigid. Pumice is composed of acidic volcanic glass with fragments of rhyolite, perlite, quartz, feldspar, and hornblende.

Scoria is basically pure volcanic lava. It resembles industrial cinders in texture in that it is angular and hard. It ranges in colour from red to black.

Diatomite is a soft, porous aggregate. It is very absorptive and can be easily broken with the fingers. In appearance, it is white to yellow in colour and angular in shape.

All these aggregates like pumice and tuff have generally poor concrete-making properties and seldom produce high strength products.

By-product lightweight aggregates: These include cinders, expanded blast-furnace slag, other industrial slags, and sintered fly-ash. Cinders are the result of high-temperature combustion of coal or coke.

Over 25 million tons of iron blast-furnace slag is used annually as construction aggregates, but only 3 million tons is expanded. Slag aggregates consist of silicates, aluminosilicates of lime and other bases formed simultaneously with the smelting of iron ore in the blast-furnace.

Expansion or 'foaming' is caused by bringing the molten slag into contact with controlled quantities of steam or compressed air. After expansion the expanded slag is crushed, screened, and stockpiled. The aggregates are angular in shape and vary in colour from dark to light grey or cream with an occasional grey particle inclusions.

Fly ash aggregate such as Lytag is produced by spraying fly ash with water and balling in a drum or disc type agglomerator. The size of pellets can be regulated by controlling the agglomeration process. The green pellets are spread over the bed of a sintering grate alongwith fuel to start the combustion. The fly ash pellets contain enough carbon to support the combustion once it has started. During sintering the carbon is burnt off and sulfur and other volatile compounds are driven out, giving a relatively inert product. A sintered fly-ash pellet usually has a brick-hard

inner core covered with a hard outer skin. It is smooth and less water absorbent than other lightweight aggregates. It is crushed to a fine or medium size, depending on the use to which it will be put.

Processed aggregate: Manufactural aggregates can also be made by expansion or 'bloating' of a suitable raw material in a rotary kiln (Patent 'Haydite' - 1917). In this method raw clay, shale, or slate is fed into the upper end of a kiln after which it travels slowly to the lower or burning end. Volatile components in the raw material gassify in the burning zone in the temperature range of 1000-1100°C and myriads of tiny cells are formed in the pyro-plastic mass. At the lower end of the kiln the mass is discharged generally into a rotary cooler. After cooling it is crushed, screened, and stockpiled. The crushing operation may be bypassed if the raw material feed is presized. The process results in the formation of a vitreous membrane, around the aggregates.

Rotary kiln expanded shale, clay, or slate may vary in shape from slightly angular to well rounded. Internally, they are composed of uniform-sized cells. They have good to excellent concrete-making properties and can achieve high strength with reasonable cement factors. These are the principal materials used as aggregate today in making structural lightweight concrete; about 75 to 85% of all

structural lightweight concrete uses these aggregates. Colour varies, as per the raw material, from tan to grey or from dull orange to light pink.

In the alternate sintering process for expanded shale and clay, the raw materials are crushed, screened, and mixed with fuel before being spread to a depth of 8 to 12 in (203.2 to 304.8 mm) on a moving grate. The grate passes under an ignition hood where the fuel is ignited. To insure combustion, air is blown or sucked through the bed.

This process causes the mass to expand and the particles fuse together into a sintered porous cake, which is cooled by a water spray or allowed to cool naturally. Subsequently the mass is broken up crushed, screened and graded. Because of the crushing process employed the aggregates are mostly rough and angular.

Vermiculite is a form of mica, in which water molecules are trapped in between thousands of paper-like sheets in chunk or granules. When this is exposed to heat at 1100°C, the water turns to steam and the sheets move apart. The granules expand to 15 to 20 times their original size. Tiny cells of dead air are formed that provide most of the insulating properties of this type of aggregate. The shiny surfaces of the particles reflect radiant heat, which contributes to their insulative properties. The finished aggregate is brown to buff in colour and has a pearly luster.

Perlite is volcanic lava or glass in origin. It pops like popcorn when it is heated because it also has water trapped in its cells. The processing involves crushing of the ore to sand size, drying, screening and blending and then heat treatment in horizontal or vertical type furnaces at temperatures of 830 to 1100°C. Expansion is from 4 to 20 times (usually 10 times) and colour changes from light grey or glossy black to almost pure white.

Lightweight aggregate properties: Size - As compared to normal-weight aggregate, lightweight aggregates are smaller. The expanded shales and slags have a top size of 3/8 to 3/4 in (9.525 to 19.05 mm).

Shape - Most lightweight aggregates are more angular in shape and rougher than normal-weight aggregates. Some tend to be irregular with harsh, pitted surfaces. However, changes in production processes have led to improved particle shape and texture.

Specific gravity - Specific gravity of lightweight aggregate is relatively low and in some cases it cannot be accurately determined. It may also vary with the size of the aggregate – larger pieces have a lower specific gravity than smaller pieces. Specific gravity of lightweight aggregate ranges from 1000 to 2400 kg/m^3 whereas for normal-weight aggregate it ranges from 2400 to 2900 kg/m^3.

Absorption – Lightweight aggregates, because of their porosity, generally absorb more water. It ranges from 5 to 20% by weight for structural lightweight aggregates and is higher for insulative lightweight aggregates such as vermiculite and perlite.

Strength – Lightweight aggregates are weaker than normal-weight aggregates. However, their strength varies widely depending on the type.

2.3 Properties of Lightweight Concretes:

2.3.1 Density and Compressive Strengths:

For all the four types of lightweight concrete densities, compressive strengths and thermal conductivities are shown in Table 2.2. For some commercial foamed concretes they are shown in Table 2.3 and for lightweight aggregate concretes in Table 2.4. Grades of concrete based on end uses are shown in Table 2.5.

2.3.2 Shrinkage:

Cement products show some small changes in their volume in response to changes in the moisture conditions. Although small in magnitude, these changes are of considerable importance. Concrete when first dried undergoes a shrinkage which is usually termed "initial drying shrinkage", and on subsequent wetting and drying, shows alternate expansion and

Table 2.3

Properties of foamed/cellular concrete

Cellular product	Bulk density (kg/m^3)	Compressive strength (28-day) (kg/cm^2)	Thermal conductivity ("K" factor)	Ref.
Aerofill	400-1600	3.52-105.6	0.65-3.65	p. 13 (1)
Betocel	400-1200	7.04-91.2	0.50-1.60	"
Calsi-crete	560 (approx.)	45.6	0.81	"
Durox	480-720	20.0-70.3	0.57-1.05	"
Elastizell	400-2400	7.03-253.0	1.1-6.[illegible]	"
Mearlcrete	240-800	3.52-66.8	0.45-1.4	"
Thermo-con	720-800	35.2	0.8-1.3	"
Cantilite	320-1120	7.03-40.7	0.4-2.3	p. 33 (1)
Poretherm	480	14.06	0.65	"
Siporex	400-704	-	0.69-1.06	"

Table 2.4

Properties of lightweight aggregate concrete

Type	Mix proportion cement: aggregate by volume	Dry bulk density of concrete (kg/m^3)	28-day compressive strength (kg/cm^2)	Drying shrinkage per cent	Thermal conductivity (kcal/ m-hr-°C)	Ref.
Clinker concrete	1:10-1:6	1040-1520	21.0-70.3	0.04-0.08	0.298-0.496	p. 83 (5)
Foamed slag concrete	1:24-1:4	960-1760	12.6-232	0.03-0.07	0.211-0.372	p. 89 (5)
-Semi dry	1:24-1:6	960-1760	12.6-63.2	0.03-0.05	0.211-0.298	"
-Fully compacted	1:8-1:4	960-1760	77.2-232	0.05-0.07	0.272-0.372	"
Expanded clay concrete						
-Fully compacted	-	960-1760	91.2-63.2	0.04-0.07	0.186-0.496	p. 95 (5)
-Semi dry						
(i) Expanded shale	1:9-1:6	1200-1360	56.2-137.0	0.05	0.347-0.421	"
(ii) Light clay	1:6	720	24.6	0.045	0.1735	"
Sintered pulverised-fuel ash concrete						
-Semi dry	1:9-1:6	1137-1215	45.7-70.3	0.035-0.045	-	p. 99 (5)
-Fully compacted	1:6-1:4	1470-1552	105-193.5	-	-	"
Expanded slate concrete						
-Semi dry (i)	1:11	560-960	14.06-21.09	0-0.03	-	p.104 (5)
(ii)	1:6	640-1280	31.6-63.2	0.04	0.124-0.248	"
-Fully compacted	1:9-1:2.8	1170-1360	91.3-281	0.094-0.078	0.347-0.421	"
Pumice concrete						
-Semi dry	1:10-1:6	656-767	21.09-38.6	0.06-0.04	0.173-0.136	"
-Fully compacted	1:4.5-1:3	1425-1470	140.6-102.0	0.10-0.08	0.322-0.298	"
Diatomite concrete	1:9-1:2.4	688-992	22.5-114.2	0.263-0.346	0.144-0.223	p.105 (5)

Table 2.5

Grades of concrete (p. 485 (29))

Grade of lightweight concrete	Compressive strength at 28-days (kg/cm^2)	Unit weight (Dry) (kg/m^3)		
		Concrete	Aggregate	
Structural	140.6-56.1	1500-1920	Coarse:	480-880
Fireproofing	56.2-140.6	1120-1600	Fine:	880-1120
Masonry	28.1-140.6	960-1600	Combined:	480-1040
Insulation	7.03-56.2	400-1120	Assorted:	96-1120

contraction, generally called "reversible moisture movement". Generally on rewetting the concrete does not expand to its original dimension. Thus the initial drying shrinkage is usually greater than the subsequent moisture expansion. Air-cured material shows higher shrinkage. This shrinkage may result in cracking of the concrete.

The British Standard for concrete blocks BS 2028:1953, gives the following limits for movements of lightweight concrete blocks -

Initial drying shrinkage	Class B	0.06%
	Class C	0.08%
Reversible moisture movement	Class B	0.05%

2.3.3 Water Absorption:

Lightweight concretes, particularly those used in blocks, are more porous and so have a higher water absorption than dense concrete. Therefore lightweight concrete exposed to the weather is not generally used without a suitable protective rendering.

2.3.4 Thermal Insulation, Compressive Strength, Tensile Strength:

Differences in apparent density as well as the effective thermal conductivity of concretes arise primarily from variations in porosity. Compressive strength and tensile strength are related to apparent density in a similar

manner. The thermal conductivity of no-fines concrete that is made with dense aggregate is 0.620 kcal/m-hr-°C, which is about half that of ordinary concrete. The thermal conductivity of lightweight aggregate concrete and of foamed concrete is shown in Table 2.6.

Table 2.6

Thermal conductivity of lightweight concrete (p. 490 and p. 501 (29))

Unit weight (Dry) (kg/m^3)	Thermal conductivity (kcal/m-hr-°C)	
	Lightweight aggregate concrete	Foamed concrete
1920	0.421-1.115	0.793
1600	0.298-0.694	0.545
1280	0.198-0.421	0.347
960	0.149-0.298	0.223
640	0.0992-0.161	0.149
320	0.0496-0.0992	0.0868
160	-	0.0496

All these are shown in Figure 2.2. Compressive strength and tensile strength dependence on bulk density are shown in Figures 2.3 and 2.4 respectively; and tensile strength dependence on compressive strength in Figure 2.5.

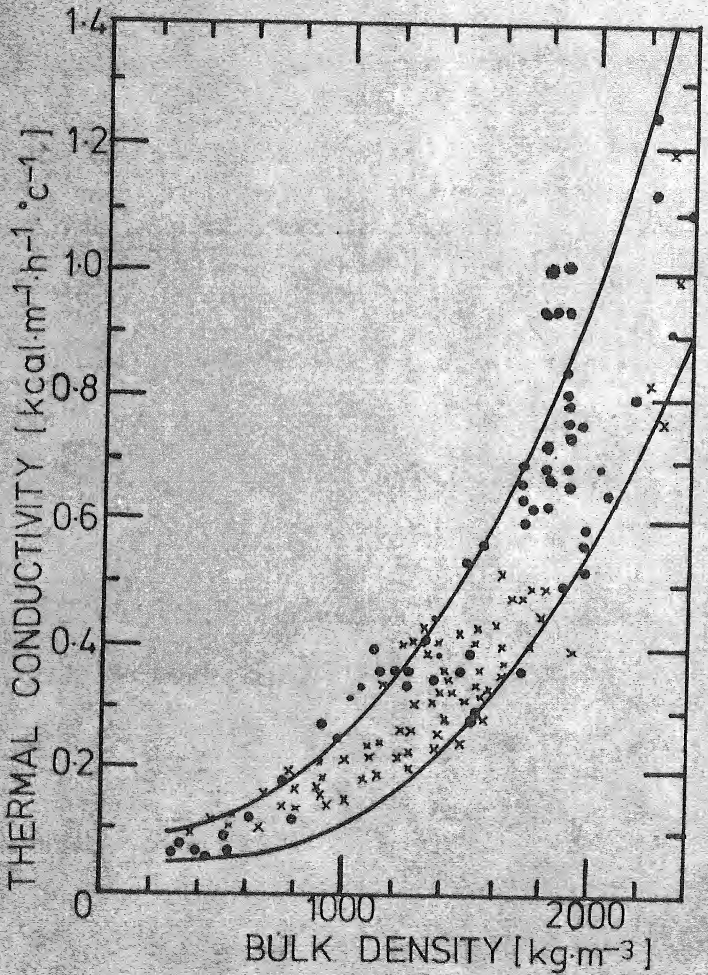


Fig. 22 THERMAL CONDUCTIVITY OF LIGHTWEIGHT CONCRETES OF VARIOUS TYPES [(10),(62)]

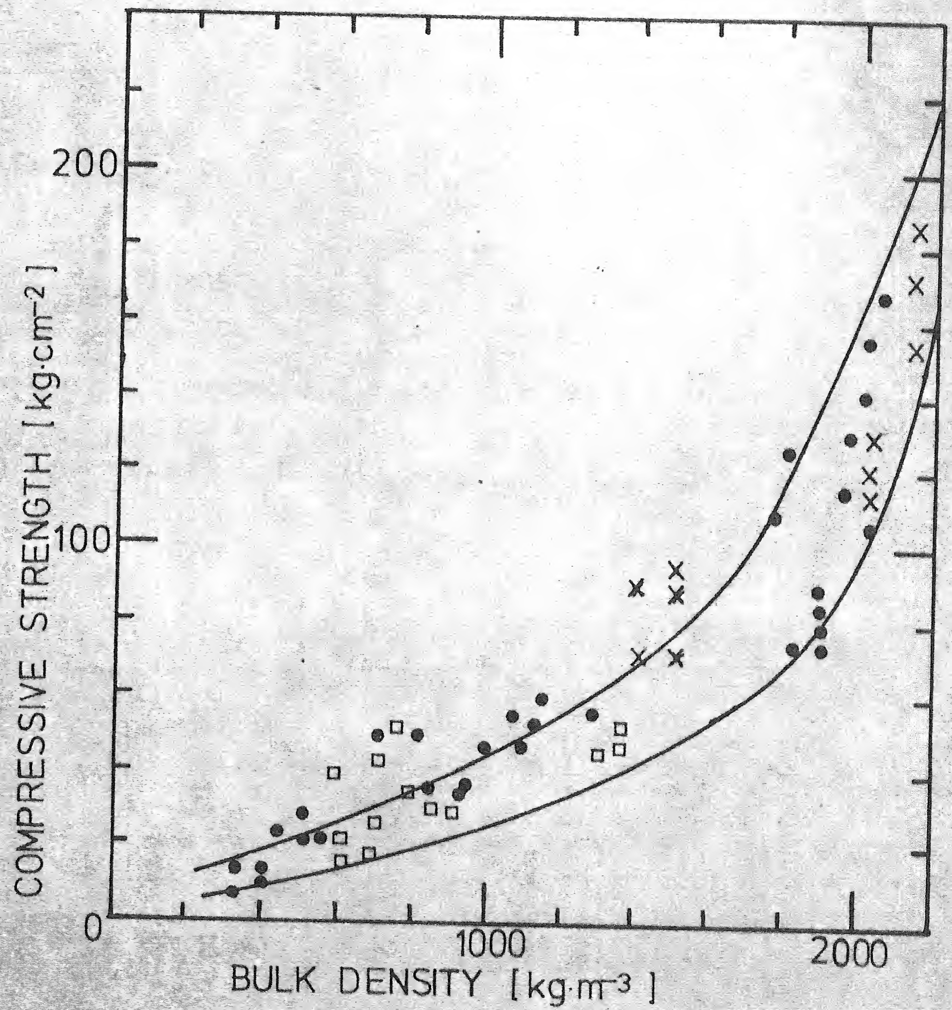


Fig. 23 COMPRESSIVE STRENGTH OF LIGHTWEIGHT CONCRETES OF VARIOUS TYPES [(10),(63),(64)]

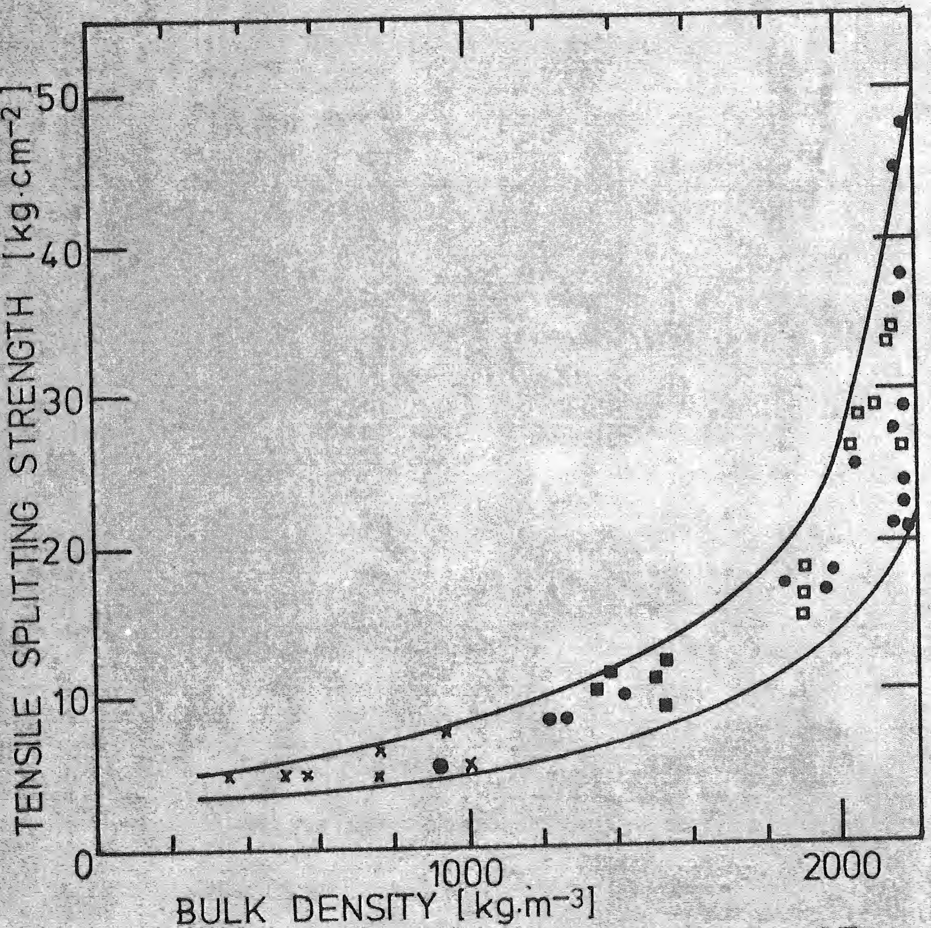


Fig. 2·4 TENSILE SPLITTING STRENGTH OF CONCRETES OF VARIOUS TYPES [10]

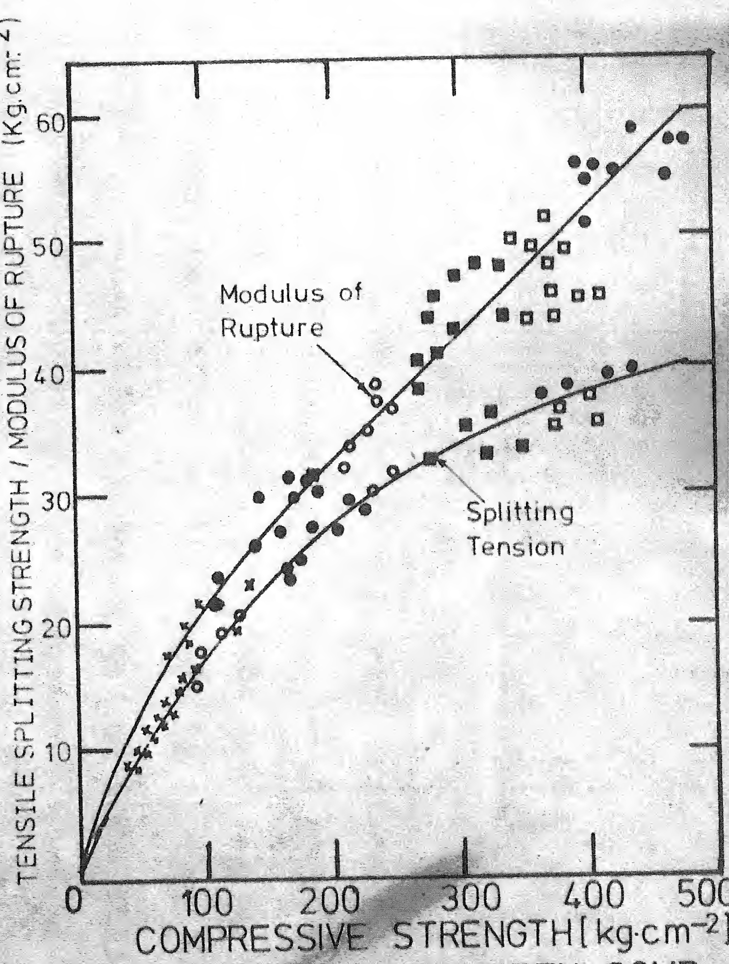


Fig.2·5 RELATION BETWEEN COMPRESSIVE AND FLEXURAL STRENGTHS OF CONCRETE [(10),(65),(66)]

2.3.5 Structural Lightweight Aggregate Concrete:

Density and compressive strength - The dry density of compacted lightweight concrete made with different kinds of aggregates varies from about 80 lb per cu ft (1280 kg/m^3) to 126 lb per cu ft (2016 kg/m^3) with cube compressive strengths ranging from 1000 psi (70.3 kg/cm^2) to 5000 psi (351.5 kg/cm^2). Lightweight aggregate can be mixed with cement in different proportions for compounding various types of lightweight concrete mixes. By adding sand to the lightweight concrete mixes, both density and compressive strength

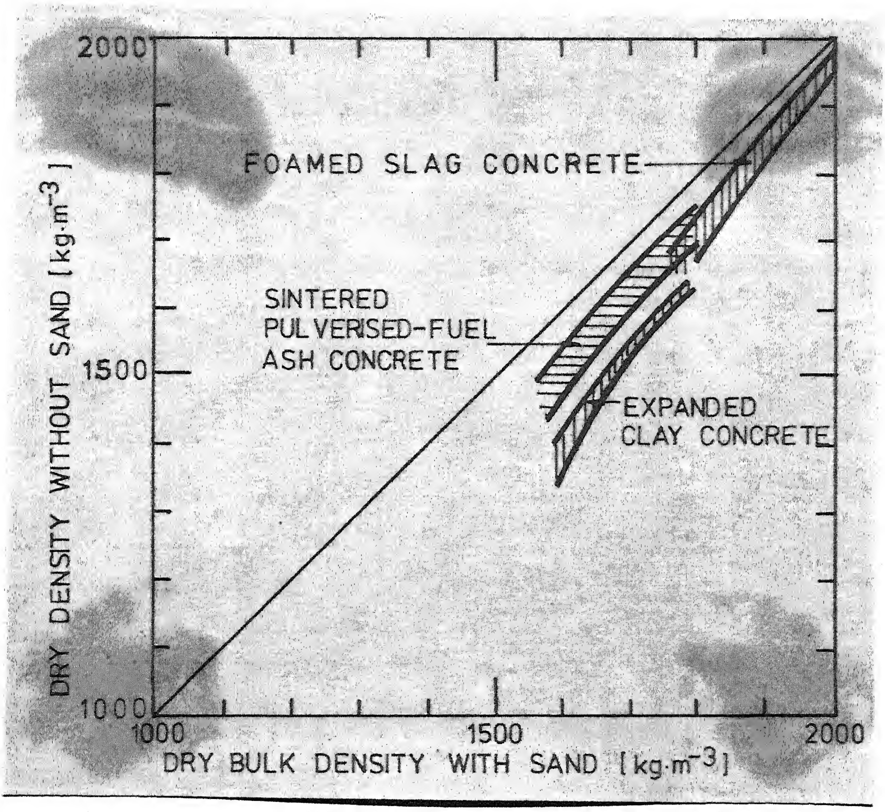


Fig. 2.6 The effect on the dry density of lightweight concretes of replacing one-half of the fine lightweight aggregate by sand, for the same cube strength, ranging from about 70 kg/cm2 to 316 kg/cm^2.

are increased considerably. The effect of the addition of sand on compressive strength and the density is shown in Figure 2.6. For foamed slag concrete of high strength and density the addition of sand has little effect on either. For the expanded clay and pulverised-fuel ash aggregates, however, the density of the concrete is increased considerably by addition of sand and, in general, is of greater importance than any increase in the compressive strength that might be achieved. For example, whereas for foamed slag concrete the increase in density due to the addition of sand might vary from $3\frac{1}{2}$ per cent for low strengths to less than 1 per cent for higher strength concretes, the corresponding increases in density for sintered clay and pulverised-fuel ash concretes may range from 10-12 per cent (6).

2.3.6 Tensile Strength and Modulus of Rupture:

Various methods have been tried to obtain at least an index of the tensile strength of concrete but none has proved entirely suitable. The cylinder splitting test (Brazilian test) has been used as a measure of the tensile strength (7). The modulus of rupture obtained for concretes made with different types of aggregate tends to vary from 250 psi (17.6 kg/cm^2) to 550 psi (38.6 kg/cm^2) for compressive strengths ranging from 1000 psi (70.3 kg/cm^2) to about 5000 psi (351.5 kg/cm^2). Exact relationship between moduli of

rupture and compressive strength is difficult to establish, but can be best represented by

$R = 8.0\sqrt{u}$

(for gravel concrete and lightweight aggregate concrete) ...(a)

$R = 9.1\sqrt{u}$ (for foamed slag concrete) ...(b)

where, R = modulus of rupture

u = cube compressive strength

Thus for low compressive strengths the ratio of modulus of rupture and the compressive strength is higher than for higher compressive strengths. The relationship of the cylinder splitting strengths to cube compressive strengths obtained from the tests concluded at the Building Research Station (Figure 2.7) can be expressed approximately by the following

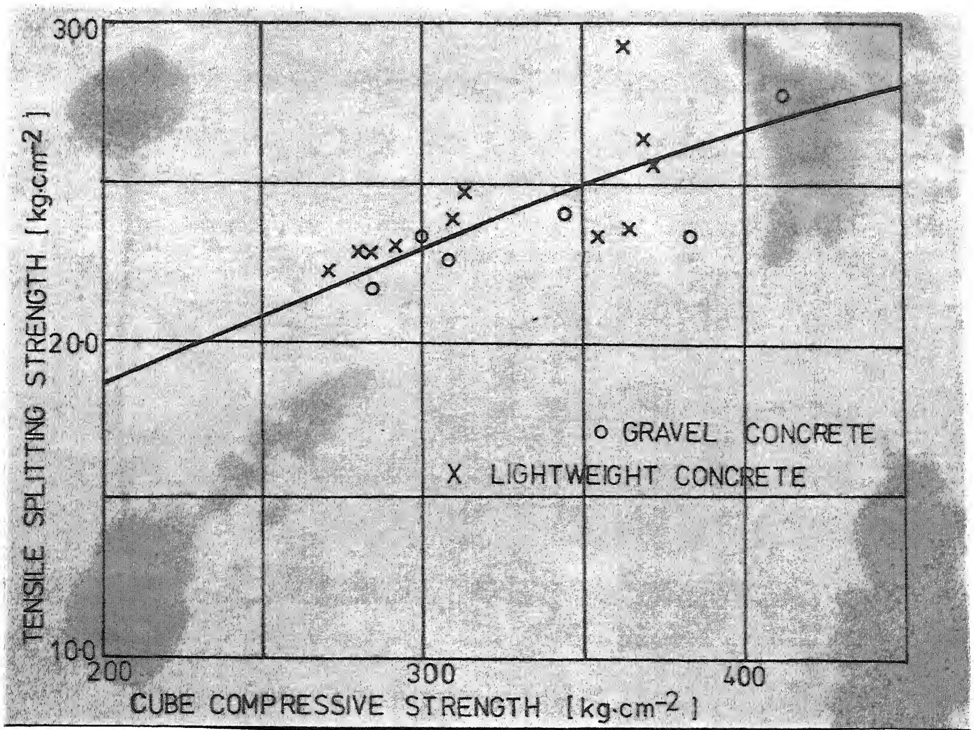


Fig. 2.7 Relationship between the cube crushing strength and the tensile splitting strength of different types of concrete

equation for all types of concrete

$$f_{sp} = K\sqrt{u} \qquad \ldots(c)$$

where, f_{sp} = cylinder splitting strength

u = cube compressive strength

K = 4.5-6.0, average 5.0.

Modulus of rupture and cylinder splitting strength do not represent the same property of the concrete although both serve as an index of the tensile strength. In general, the cylinder splitting strength is about 60 per cent of the modulus of rupture.

Tests by Hanson (8) indicate that the tensile strength of concrete is greatly affected by its moisture content. The split cylinder tensile strength of saturated lightweight concrete is considerably higher than the average tensile strength of the same concrete tested in an air-dry state. The results obtained in a saturated state are also more uniform. On the other hand for denser gravel aggregate concrete the tensile strength was found to be slightly higher for the dry than for the saturated material.

The tensile strength is an important criterion of the susceptibility to cracking in different types of concrete. Since concrete is a highly heterogeneous material, its tensile strength tends to vary considerably and its composition will affect not only the tensile stress at which cracking occurs but also the mechanism of the fracture process itself. For

example in gravel concrete, the aggregate being stronger than the cement bond the failure occurs as a result of the breakdown of the bond between the matrix and surface of the aggregate or by fracture of the matrix itself rather than by fracture of the aggregate. The aggregate particles are not very compressible, and in general are not subjected to appreciable shrinkage. The tensile stresses induced in the matrix through its shrinkage due to loss of moisture are therefore, all the more important and increase the tendency of the matrix to crack. But shrinkage would cause lower tensile stresses in the matrix of lightweight aggregate concrete than in gravel concrete because the resistance of lightweight aggregate particles to local deformation is less.

2.3.7 Modulus of Elasticity:

For the same compressive strengths, the modulus of elasticity of lightweight concrete is in general considerably lower than that of dense, gravel concrete (9). For concrete of high strength the percentage difference is somewhat greater than for weaker mixes, but in general the E-value of lightweight concrete ranges between 1/3 and 2/3 of the value of the corresponding gravel concrete mix. The modulus of elasticity increases with the cube compressive strength and with the density of the concrete. Various empirical expressions have been derived to relate the two properties.

For lightweight concrete it varies between about 1.0 and 3.0 x 10^6 psi (0.703 and 2.109 x 10^5 kg/cm^2) under short duration loading depending on the strengths and type of aggregates.

The modulus of elasticity is of special importance for structural lightweight concrete construction because of its effect on deflections of the flexural members, on the distribution of internal forces in the cross-section of compression members and on the critical load in the case of members liable to failure due to elastic instability, where the lower E-value of lightweight concrete has an unfavourable influence. On the other hand, the resistance of lightweight concrete members to impact loads may be enhanced by their lower modulus of elasticity.

2.4 Pozzolanas and Pozzolanic Cements:

Pozzolana is a natural or artificial material containing some form of silica in a reactive form. It is essential that pozzolana be in a finely divided state as it is only then that silica combines with lime in the presence of water to form stable calcium silicates which have the cementitious property. Most common pozzolanic materials are: volcanic ash, pumicite, calcined diatomaceous earth, burnt clay, fly ash etc. Artificial pozzolanas are prepared by burning the raw materials in a kiln under controlled

conditions. Pozzolanic cements are prepared by grinding together hydrated lime and pozzolana (10,11).

2.4.1 Chemical Composition of Pozzolana and Pozzolanic Action:

The chemical composition of natural pozzolanas and artificial pozzolanas vary over a wide range as shown in Table 2.7 and Table 2.8 respectively. In natural pozzolanas and in low-lime fly ashes the sum of SiO_2, Al_2O_3, and Fe_2O_3 is well above 70 per cent of the total, the minimum value as per ASTM C618. However, chemical composition is of little importance, in determining its cementation properties, the crucial requirement is that substantial portion of pozzolana should be in the form of amorphous silica, such as opal and volcanic glasses, which is reactive with lime at ambient temperatures.

The pozzolanic action is a combination of physical and chemical processes. Siliceous compounds after combining with hydrated lime form stable cementing substances of uncertain composition involving water and calcium silicate.

2.4.2 Properties of Lime-Pozzolana Mortars and Lime-Pozzolana Reaction:

The setting time of lime-pozzolana mixes is variable and though the initial set may occur in 1-3 hours, the final set does not usually occur in less than 10-12 hours. For a given material the strength development is a function of

Table 2.7

Percentage composition of volcanic ash - natural pozzolanas (11)

Pozzolanas	Ignition loss	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	SO_3
Rhenish trass	10.1	54.6	16.4	3.8	0.6	3.8	1.9	5.1	3.9	0.4
"	8.5	54.8	17.2	4.4	0.6	2.3	0.9	7.0	3.8	0.1
Bavarian trass	14.5	57.0	10.9	5.6	0.5	6.0	2.2	1.8	1.5	0.2
Santorin earth	4.9	63.2	13.2	4.9	1.0	4.0	2.1	3.9	2.6	0.7
"	3.1	65.2	12.9	6.3	-	3.2	1.9	2.6	4.2	-
Rome: Segni	9.6	44.1	17.3	10.7	-	12.0	2.0	1.4	3.1	-
Segni	5.3	48.2	21.9	9.6	-	7.5	3.2	4.1		0.3
S. Paolo	4.1	45.2	20.0	10.7	-	9.8	3.8	6.2		0.3
Naples: Bacoli	4.8	55.7	19.0	4.6	-	5.0	1.3	3.4	3.9	-
Baia	4.4	59.5	19.3	3.3	-	2.1	0.2	11.3		0.2
Rumanian trass	13.9	62.5	11.6	1.8	-	6.6	0.7	2.9		-
Crimean tuff	11.7	70.1	10.7	1.0	-	2.5	0.3	3.7		-
U.S.A. rhyolltic	3.4	65.7	15.9	2.5	-	3.4	1.3	5.0	1.9	-
Pumicite	4.2	72.3	13.3	1.4	-	0.7	0.4	1.6	5.6	Trace

Table 2.8

Percentage composition of some artificial pozzolanas (12)

Pozzolana	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O and K_2O	SO_3	Ignition loss
Burnt clay	60.2	17.7	7.6	2.7	2.5	4.2	2.5	1.3
Spent oil shale	51.7	22.4	11.2	4.3	1.1	3.6	2.1	3.2
Burnt gaize	88.0	6.4	3.3	1.2	0.8	-	Trace	-
Raw moler	66.7	11.4	7.8	2.2	2.1	-	1.4	5.6
Burnt moler	70.7	12.1	8.2	2.3	2.2	-	1.5	-
Raw dolomite	86.7	2.3	1.8	Trace	0.6	0.4	-	8.3
Burnt dolomite	69.7	14.7	8.1	1.5	2.2	3.2	-	0.4
Fly ash (U.S.A.)	47.1	18.2	19.2	7.0	1.1	3.95	2.8	1.2
Fly ash (British)	47.4	27.5	10.3	2.1	2.0	5.7	1.8	0.9

lime-pozzolana ratio. At early ages the maximum strength is obtained with a lime-pozzolana ratio of about 1:4, but for longer ages (one year) it is with 1:3 to 1:2. The rate of strength development is appreciably increased by a rise in the temperature. Pozzolana that is inert at 15°C may show satisfactory results at 30-40°C (Table 2.13). Pozzolana-lime mortars attain a much higher ultimate strength when cured in water than in air, though the initial effect is reverse. Moise curing is essential whereas rapid drying is most injurious for high strength development.

Dempster and Ritchie (13) have found that grinding produces a disturbed layer on the surface of siliceous particles. This external disturbed layer is highly reactive and forms calcium silicate hydrate with calcium hydroxide in the presence of water. This layer of calcium silicate hydrate travels gradually to the center of pozzolana particle. The whole process is very slow and takes a very long time to complete. X-ray work carried out by Malquori (14), Lea (15) and Stratling(16) found the presence of $4CaO \cdot Al_2O_3$ aq.; $3CaO \cdot Al_2O_3 \cdot 6H_2O$, $3CaO \cdot 2SiO_2$ aq. and solid solution of $3CaO \cdot SiO_2$ with $CaO \cdot SiO_2$ aq., in the hydrated lime pozzolana mix. Some properties of lime-pozzolana mix are shown in Tables 2.9, 2.10, 2.11, 2.12 and 2.13.

Table 2.9 (11)

Pozzolana	Maximum strength, (kg/cm^2)		Percentage of lime (in the lime-pozzolana mix) giving maximum strength	
	Bending	Compression	Bending	Compression
Trass	38.6	115	35	26
Roman	35.5	130	32	28

Table 2.10 (11)

Effect of pozzolana: Lime ratio on strength of mortars

Pozzolana	Mix proportions (weight)			tTensile strength (kg/cm^2)			
	Hydrated lime	Pozzolana	Standard sand	7 days	28 days	90 days	1 year
Burnt shale	1	1	6	7.51	14.55	24.0	36.6
	1	2	9	9.34	22.6	32.3	39.4
	1	4	15	14.28	26.1	36.1	37.5
Trass	1	1	6	15.0	25.4	31.4	33.6
	1	2	9	15.8	27.4	29.9	34.8
	1	4	15	16.45	25.5	29.0	30.4

Table 2.11 (11)

Tests on 0.8:1:1.5 hydrated lime:pozzolana:standard sand mortars

Pozzolana	Percentage residue on 170-mesh sieve	Tensile strength (kg/cm^2)		Compressive strength (kg/cm^2)	
		7 days	28 days	7 days	28 days
Italian	33.8	15.05	25.0	98.7	190.3
Trass	35.5	8.43	17.9	78.6	119.5
Moler	49.2	12.5	18.95	28.9	69.6
Pumice	29.2	5.06	18.95	34.8	104.0

Table 2.12 (11)

Effect of fineness of grinding of pozzolanas 1:4:15 lime:trass:graded sand mortars (14.8 pe cent water)

Percent residue on 170-mesh sieve	Strength (kg/cm^2)			
	Bending		Compression	
	28 days	1 year	28 days	1 year
43.0	12.85	26.1	24.0	83.5
14.5	18.9	33.4	35.1	89.9
3.0	21.5	33.7	48.5	102.5

Table 2.13 (11)

Effect of temperature on strength of lime-pozzolana mortars (1:1:6 Lime:Pozzolana:Standard sand mortars of dry consistence)

Pozzolana	Tensile strength (kg/cm^2)							
	7 days				28 days			
	0°	12°	25°	35°	0°	12°	25°	35°
Santorin earth	0	0.562	3.09	7.24	0	6.04	22.25	28.[illegible]
Burnt shale	3.375	6.04	10.6	18.0	6.46	16.92	24.45	32.[illegible]

2.5 Accelerated Curing (19):

The curing of concrete can be accelerated by raising its temperature. This can be done in practice by placing the concrete in hot water, steam, autoclave (high pressure) or in an oven under high humidity by increasing the rate of the hydration reactions. For portland cement products curing in an autoclave at about 175°C for 10 hours yields strengths comparable to those obtained in 28-days at ordinary temperature. Accelerated curing effect is found to a greater extent in pozzolanic materials. This permits the use of factory methods for the production of precast products; the demand for such methods seem likely to increase on account of the growth of prefabrication in building. Products can be made which are in some respects superior to those of normally cured concrete; the chemical resistance and the dimensional stability can be much improved. Also, there is a possibility of replacing the cement partly or wholly by waste materials, which are unreactive at ordinary temperatures but which possess cementing properties at higher temperatures. Steam curing can be classified as: (i) low pressure steam-curing carried out at temperatures up to 100°C, under atmospheric pressure, (ii) high pressure steam-curing carried out in autoclaves using saturated steam, usually at temperatures around 175°C.

The factors governing the choice of the curing cycle, and the physical and chemical properties of the product, have been discussed by Nurse (17,18). There has been some disagreement as to the optimum heating rate and as to whether a period of initial curing is necessary. Nurse concluded that either an initial period of few hours at room temperature or a slow rate of heating was desirable to avoid possible interference with the normal setting process, since there was some evidence that such interference could lower the ultimate strength reached. Saul (21) and Nurse (18) concluded that satisfactory results could be obtained at all temperatures up to 100°C, provided the initial heating was not too rapid, and there was no basis for the view that lower strengths were obtained at 80-100°C than below or above this range, considered by earlier workers. Maximum safe rate of heating for steam-cured concrete and strength versus (curing time x curing temperature) plots for portland cement concrete are available in literature (21,18). Similar plots for other pozzolanic cement concrete can be obtained.

In order to include the effect of reactive aggregates, pozzolanas along with portland cement a factor expressing "maturity" of the concrete should be used, which is the product of the curing time and the temperature above -10°C. These procedures have been studied by Mironov and Gamin (22). Curing in steam at atmospheric pressure or

in hot water can be used to forecast the long-term strength of a normally cured cement or concrete (23,24,25).

Low pressure steam-cured concrete continues to gain in strength after the curing cycle has been completed, and the final strength, although slightly reduced, is comparable to that of normally cured concrete, provided the initial heating rate has not been excessive. In dimensional stability it does not differ significantly from normally cured concrete. Resistance to sulphate attack may be improved by curing at 100°C or by high pressure steam-curing. Steam-curing reduces drying shrinkage. Tests are quick and results reliable.

2.6 Additives:

Many chemicals have a pronounced effect on the setting of cement, they either increase or reduce the early strength and the rate of hardening and hence are called 'accelerators' or 'retarders'. Calcium chloride, magnesium chloride, ferric chloride etc. are used in small amounts (maximum 2% of the weight of the cement) as accelerators. Sodium aluminate and sodium fluoride are added for very fast setting times (1-3 minutes). The rate of setting is very sensitive to the quantity of triethanolamine, a very small amount increases the rate of setting considerably and an addition of 0.2% can cause a flash set (26). Increased

early strength during cold weather expedites demoulding and stripping operations, permits early loading of anchor devices, and affords resistance to damage by frost-action or freezing temperatures at an early age.

The amount of calcium chloride that is used should not exceed 2 per cent by weight of cement in a mix. Under temperate conditions, 1 per cent should suffice, whereas if less than 1/2 per cent is used the set could be retarded for a short period. Steam-cured concrete strength is higher at all ages when this accelerator is used (27). An admixture of calcium chloride reduces the resistance of concrete to sulphate attack. The chemical increases the resistance of concrete to erosive and abrasive action, and it increases the expansion that is caused by alkali-aggregate reaction (28). Calcium chloride increases shrinkage from 10 per cent to possibly 70 per cent, but decreases the moisture loss under drying conditions. In steam-cured prestressed concrete, the calcium chloride causes electrolytic corrosion of pretensioned high-tensile and hard-drawn steel wires. The corrosion is less severe when products of this kind are cured in hot water, and it does not occur when steam curing is used on its own. Other admixtures used consist of foaming agents and either a setting accelerator for foamed concrete containing cement or a hydration retarder for mixes containing ground quicklime in conjunction with hydrated

lime and silica flour. The rate of hardening of foamed concrete is increased by the use of high-early-strength portland cement or by using the mixing water at a temperature between 24° and 66°C. It is doubled, more or less, by the use of one of the setting accelerators that are listed in Table 2.14.

Table 2.14

Setting Accelerators (29)

Admixture	Amount per cent by weight of cement
Aluminium sulphate	1 to 2
Calcium chloride	2 to 3
Sodium carbonate crystals	3/4 to 1½
Sodium hydroxide	1/2 to 1
Sodium silicate (20 per cent low-alkali solution)	4 to 6
Triethanolamine	1/10 to 1/8

2.7 Rice Husk and Rice Husk Ash:

2.7.1 Rice Husk:

The rice hull surrounds the edible grains of rice for the protection against birds and insects. Rice hull is 5-8 mm in length, 2-3 mm in width and about 1/2 mm in

thickness. These are the woodlike material in which silica network is embedded. The silica in the hull is dispersed throughout in a highly porous and extended skeleton like network, its concentration is higher near the inner and outer surfaces. The packing density of hulls is very low, of the order of 96-160 kg/m^3 (4). Rice hulls vary somewhat in composition depending on the rice variety, soil and other conditions of growth. However the main constituents are cellulose, lignin and inorganic ash residue.

Rice husk is used as animal feed, fuel in rice mill boilers and live-stock bedding, the remaining is disposed of by field-burning. Husk can also be utilized to make activated charcoal (30,31,32,33), silicon carbide (34), silicon tetrachloride (35), urea formaldehyde bonded boards (55), rice bran oil, fillers for plastics (36), zeolite molecular sieves (37), polyethylene bonded boards (38), for oil contaminated water treatment (39), particle boards (phenolic binder) (40), polystyrene composite-injection moulded furniture (41), heat insulating mixture for cast-iron melt in ladle (42), furfural (43) etc.

2.7.2 Rice Husk Ash:

Depending on the extent of combustion of the hulls and the trapped carbon in the ash, the ash content of the hull ranges from 20-30 per cent. The chemical composition of

rice hull ash as reported in literature is given in Table 2.15. The rice hull ash is highly siliceous, moreover, the silica is present in a highly porous, amorphous or distorted multiple polymorphic, crystalline forms (44,4). The structural forms are dependent on the burning conditions; boiler and field burning gives relatively crystalline and controlled burning at lower temperature gives relatively amorphous one. The ash is of very low bulk density and is highly reactive. In this respect it is a unique starting material which may have very interesting applications. As a matter of fact it has been used in making porous refractories (4,48), fillers for plastics and rubbers (49,50,51,52), lining for ingot molds (42,53), acoustical boards and ceiling for building (38,40,54,55), porous media (56), silicon carbide (34), silicon tetrachloride (35), zeolite molecular sieves (37), building material (57), high strength cement (44,58) and concrete (59).

Rice husk ash has the properties of lightweight aggregate (filler), like pozzolanic material it can combine with hydrated lime to form hydrated cementitious calcium silicates which can be aerated and autoclaved.

Rice husk ash is a waste product of rice mills and is available in large quantities, almost free, at mill sites. Vast resources of rice husk ash, having above-mentioned properties should be amenable to exploitation for manufacture

Table 2.15

The chemical composition of rice hull ash as reported in literature

	Houston 1962 (45)	Siam Cement Co. (46)
Oxide	wt. %	wt. %
SiO_2	86.9-97.3	88.66
Al_2O_3	-	1.48
Fe_2O_3	Trace-0.54	0.36
SO_3	0.1-1.13	Trace
CaO	0.2-1.5	0.75
MgO	0.12-1.96	3.53
CO_2	-	0.51
K_2O	0.58-2.50	-
Na_2O	0-1.75	-
P_2O_5	0.2-2.85	-
Cl	Trace-0.43	-
Loss in ignition	-	3.80

of useful building materials (4).

Work by Maksoud et.al. (47) also shows that rice hull ash can be utilized to make load-bearing constructional units. The completely decarbonized ash residue of rice hulls was ground and mixed with 15 per cent hydrated lime and subjected to different conditions of hydrothermal treatments. Results showed that a calcium silicate hydrate probably an ill defined form of tobermorite, is the main component of the cured samples together with small residual amounts of hydrated lime and silica. The products obtained showed reasonable values of apparent porosity, bulk density and water absorption as well as high compressive strength. These properties became more improved on treating the materials at higher steam pressure, a case which is probably connected with the formation of a more well defined form of tobermorite at such conditions — as suggested by DTA results.

The cement obtained from rice husk ash, 'ASHMOH', has cement sand mortar cube strength values comparable to that of portland cement ones. Setting time also lies in that of pozzolanic cement range (60), but both initial and final setting time can be reduced (by addition of certain additives) and can be brought close to that of portland cement.

In summary:

(i) Rice husk ash is a very lightweight porous filler (aggregate)

(ii) Ground rice husk ash-lime mixture gives a cement (ASHMOH) which is lighter in weight than ordinary portland cement and has comparable cementing properties.

Clearly it should be possible to exploit these characteristics of the rice husk ash filler and cement to prepare lightweight structural and insulative concrete, which is the objective of this investigation.

CHAPTER - 3

OBJECTIVE OF PRESENT WORK

The main aim of this work was to study the feasibility of making structural and insulative lightweight concretes using rice husk ash, ASHMOH cement and sand. Rice husk ash, ASHMOH and sand were characterized with respect to bulk density, specific gravity, particle size distribution, and specific surface area etc. Optimum water content for mixes of different proportions of these ingredients was determined so as to maximize the strength. Both tensile and compressive strength of these concretes were obtained and checked if they met the specifications. At those bulk density levels where the strengths were low various additives were added to the mixes to reach the specified strengths. Steam-curing time effect was studied along with normal 28-days curing under water. Steam-curing at one atmosphere was used to compare with 28-days strength. Some samples of portland cement-sand mortars were also prepared to compare with Ashmoh-sand mortars. Setting time of Ashmoh and additives' effect on it were studied.

In brief the aim of this work was to study:

(i) The manufacture of lightweight concrete spectrum in density range 1000-2000 kg/m^3.

(ii) Strength characteristics of these concretes, both tensile and compressive and the ratio of tensile strength to compressive strength at different bulk densities.

(iii) Steam-curing time effect at one atm. pressure.

(iv) Effect of additives, on strength and setting time of concrete mixtures.

CHAPTER - 4

MATERIALS AND METHODS

4.1 Materials:

Materials used for making lightweight concrete samples were sand, rice husk ash, Ashmoh cement, portland cement, and additive chemicals ($CaCl_2$, $MgCl_2$ etc.).

4.1.1 Sand:

Sand was the dense filler aggregate. The sand used was Kalpi sand which is coarse and rough (unlike the Ganga sand). It was sieved (-16 mesh) and was washed with water to remove all the clay matter. The sand was dried and stored. The particle size distribution of this sand is plotted in Figure 4.1. True density (specific gravity) of sand was 2532 kg/m^3 and apparent or tapped bulk density was 1626 kg/m^3.

4.1.2 Rice Husk Ash:

Rice husk ash is a light, porous aggregate filler. It was obtained from a rice mill in Uttari Pura, a village 45 km North of Kanpur on Delhi-Calcutta National Highway No. 1. It was neither unburnt nor fully burnt hence white-grey in colour. It was sieved through a 20-mesh size screen

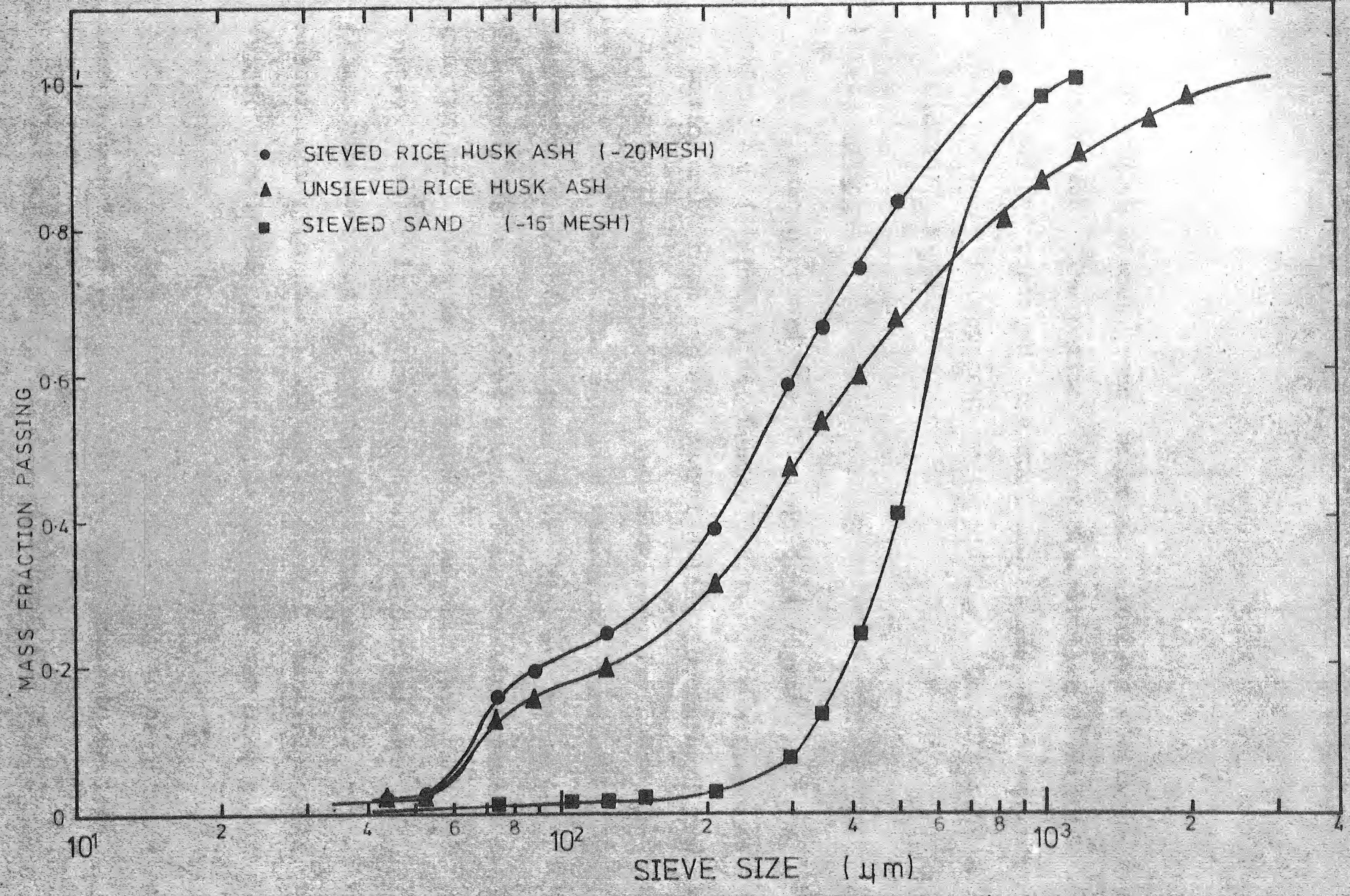


Fig. 4·1 Cumulative Particle Size Distribution of Sand & Rice Husk Ash.

to get rid of stones, sand, charcoal particles giving uniform rice husk ash. The particle size distribution of sieved (-20 mesh) and unsieved rice husk ash is also plotted in Figure 4.1. Bulk (apparent or tapped) density of rice husk ash was 327.9 kg/m^3.

4.1.3 Ashmoh:

Ashmoh cement was obtained from Vigyan Shikshan Kendra, Aau (Atarra, Dist. Banda, U.P.). It was prepared by mixing rice husk ash and hydrated lime (commercial grade) in a proportion of 70:30 and grinding for five hours in 3' x 3' ball mill. The ash used was of the same colour and quality as that obtained from Uttari Pura and hence the colour of Ashmoh was light grey. True density (specific gravity) of Ashmoh is 2082.5 kg/m^3 and bulk (apparent or tapped) density is 952 kg/m^3. Specific surface area of Ashmoh was measured by the standard Blaine surface area measurement apparatus. As the calibrated standard sample was not available ordinary portland cement was used as standard and its surface area was assumed to be 2250 cm^2/g. Surface area of the Ashmoh cement was found to be 3850 cm^2/g. Ashmoh cement was stored in sealed containers to protect it from moisture.

4.2 Methods:

4.2.1 (a) Rings and Cubes:

Rings were cut from 3" (7.62 cm) O.D. M.S. pipe and machined (bored) to internal diameter of 7 cm, height of the ring was half its diameter i.e. 3.5 cm. These rings were used as moulds to make discs of compacted 'mix' samples which were used to determine tensile strength (cylinder splitting test).

Brass split cube moulds (face area 50 cm^2) were used to make cube samples of the compacted 'mix'.

(b) Mixing Procedure: Rice husk ash, sand, Ashmoh were batch-mixed to get a uniform mixture and water was added in measured quantity and mixed thoroughly to get a uniform mix. This mix was covered with wet-moist cloth so that it did not 'dry-up' and had the same water content throughout while making the discs or cubes. This mix was hand-moulded and rammed gently in moulds and sufficient care was taken to avoid lamination in the samples. Excess material was levelled off.

4.2.2 Hardening:

The sample was allowed to set in the mould for 24 hours, after that it was demolded and kept under moist cloth for another 24 hours to complete the initial hardening.

4.2.3 Curing:

After the sample was hardened in the above-mentioned manner, it was cured for further hardening or strength development. This was carried out by either water-curing or steam-curing.

Water Curing: The samples were immersed in water and kept for 28 days. Depending on the time of the year the water temperature ranged from approximately 15 to 30°C.

Steam Curing: The samples were kept in saturated steam at 1 atm for specified number of hours to reach nearly the same 'maturity' stage as accomplished by 28 day water curing. After curing the samples were dried, inspected for flaws and measured for bulk density and then tested for strength. If tested wet the strength values were higher and more uniform than for the dry samples.

4.3 Testing:

4.3.1 Bulk Density and True Density (Specific Gravity):

Bulk density of rice husk ash, Ashmoh and sand was determined by taking a suitable amount of the material in a measuring cylinder and tapping the sample on a vibratory table. After 5-10 minutes or so when the bed did not compact further its volume was noted. From the known mass and the bed volume the bulk density was computed.

The true density (specific gravity) was measured in a specific gravity bottle using acetone for Ashmoh cement and water for the sand and rice husk ash.

4.3.2 <u>Surface Area</u>: Specific surface area of Ashmoh was determined using Blaine apparatus and a standard sample of portland cement. The method involves preparation of a uniformly packed bed of 0.5 ± 0.005 porosity in the standard cell and time taken for a fixed volume of air (at constant temperature) to pass through this bed was noted. The formula used is:

$$S = S_s \frac{\rho_s(1 - e_s)}{\rho(1 - e)} \cdot \frac{\sqrt{e^3}}{\sqrt{e_s^3}} \cdot \frac{\sqrt{\eta_s}}{\sqrt{\eta}} \cdot \frac{\sqrt{T}}{\sqrt{T_s}} \qquad \ldots(d)$$

where,

S : specific surface area in sq cm/g of the test sample

S_s : specific surface area in sq cm/g of the standard sample used in calibration of the apparatus. Here ordinary portland cement was used; (S_s = 2250 sq cm/g)

T : measured time interval in seconds of manometer drop for test sample; (Note)

T_s : measured time interval in seconds of manometer drop for standard sample used in calibration of the apparatus; (Note)

η : viscosity of air in poise at the temperature of test of the test sample; (Note)

η_s : viscosity of air in poise at the temperature of test of the standard sample (portland cement) used in the calibration of the apparatus; (Note)

e : porosity of prepared bed of test sample; (Note)

e_s : porosity of prepared bed of standard sample (portland cement); (Note)

ρ : specific gravity of test sample was for Ashmoh, 2.0825

ρ_s : specific gravity of standard sample used in calibration of apparatus (Assumed to be 3.15 for portland cement)

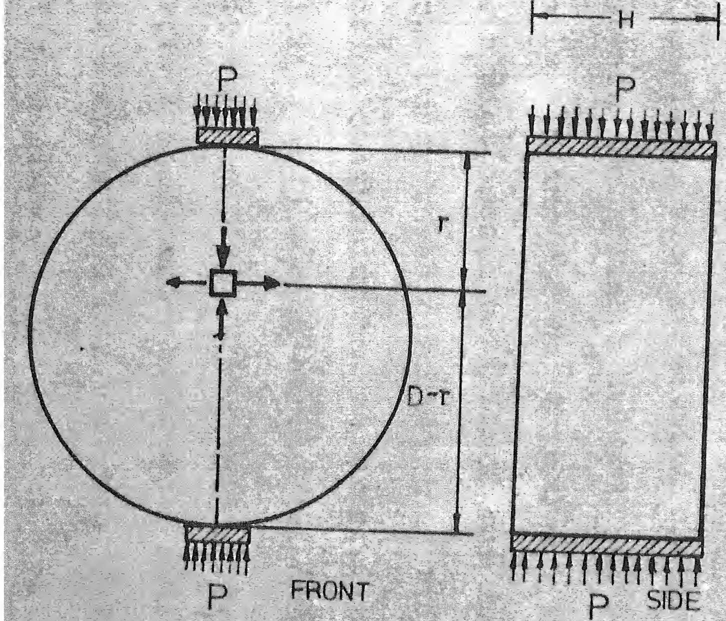
When the measurements are done at the same temperature, and the same packed bed porosity is used (0.5 $\pm$ 0.005) we have the simplified equation

$$S = S_s \frac{\rho_s}{\rho} \cdot \frac{\sqrt{T}}{\sqrt{T_s}} \qquad \text{...(e)}$$

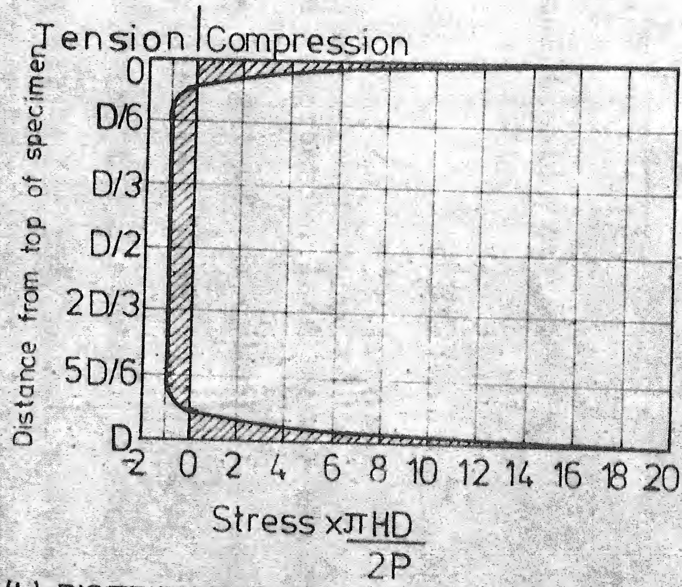
4.3.3 Splitting Test (Brazilian Test) (10):

The cylindrical pellets are placed such that their axis is horizontal between the platens of the testing machine as shown in Figure 4.2(a) and compression load is increased until failure by splitting along the vertical diameter takes place.

If the load is applied along the generatrix then an element on the vertical diameter of the cylinder (Figure 4.2(a)) is subjected to a vertical compressive stress of



(a) THE SPLITTING TEST



(b) DISTRIBUTION OF HORIZONTAL STRESS IN A CYLINDER LOADED OVER A WIDTH EQUAL TO 1/12 OF THE DIAMETER [(10),(61)]

Fig. 4·2

$$\frac{2P}{\pi HD}\left[\frac{D^2}{r(D - r)} - 1\right]$$

and a horizontal tensile stress of

$$\frac{2P}{\pi HD}$$

where,

P is the compressive load on the cylinder

H is the height of the cylinder

D is the diameter of the cylinder

and r and (D-r) are the distances of the element from the points of application of two loads respectively.

However, immediately under the load a high compressive stress is induced, and in practice narrow strips of a packing material, such as plywood or cardboard, are interposed between the cylinder and the platens. These strips are usually 1/8 in (3.2 mm) thick, and it is convenient to make their width equal to 1/12 of the diameter of the cylinder. Under these circumstances the horizontal stress on a section containing the vertical diameter is as shown in Figure 4.2(b) (61). High horizontal compressive stress exists in the vicinity of the loads but, as this is accompanied by a vertical compressive stress of comparable magnitude producing a state of biaxial stress, failure in compression does not take place.

The strength determined in the splitting test is believed to be closer to the true tensile strength of the

concrete than the modulus of rupture value. As evident from Figure 4.2(b) the splitting occurs due to tensile stress equal to

$$\text{T.S.} = \frac{2P}{\pi HD} \qquad \ldots(f)$$

Another advantage of the splitting test is that the same type of sample can be used for compressive strength measurement if it is cast as a cylinder.

4.3.4 Cube Compressive Strength:

Concrete or mortar cubes having 50 sq cm face-area after curing and drying were placed between the platens of a universal testing machine or standard RIEHLE cube testing machine. The load was applied at the rate of 2000 lb/in^2/min (140.6 kg/cm^2/min) as for as possible but due to non-linearity of the stress-strain relationship for concrete at high stresses, the rate of increase in strain must be increased progressively as failure is approached, i.e. the speed of the movement of the head of the testing machine had to be increased. This could be done only with a hydraulically operated machine. Hence, RIEHLE cube testing machine was used for most of the tests. The load at which failure occurs divided by the face-area of the cube (50 cm^2) gives the cube compressive strength of the mortar or concrete.

4.3.5 <u>Setting Time (10)</u>:

(a) <u>Consistence of Standard Paste</u>: For the determination of the initial and final setting times neat cement pastes of a standard consistence were used. It was, therefore, necessary to determine for any given cement the water content of the paste which would produce the desired consistence.

The consistence was measured by the Vicat apparatus using a 10 mm diameter plunger fitted into the needle holder. A trial paste of cement and water was mixed in a prescribed manner and placed in the mould. The plunger was then brought into contact with the top surface of the paste and released. Under the action of its weight the plunger penetrated the paste, the depth of penetration depended on the consistence. This was considered to be standard, as per B.S. 12:1958 when the plunger penetrated the paste to a point 5 to 7 mm from the bottom of the mould. The water content of the standard paste was expressed as a percentage by weight of the dry cement. The usual range of values; for portland cement is between 26 and 33 per cent, and for Ashmoh cement between 45 and 50 per cent. For Ashmoh cement used in this work it was 47 per cent.

(b) <u>Setting Time</u>: The setting times were measured using Vicat apparatus with different penetration attachments.

For the determination of initial set a round or square needle with a cross-sectional area of 1 sq mm was used.

This needle, acting under a prescribed weight, was used to penetrate a paste (made by using 85 per cent of the water required for a paste of standard consistence) placed in a special mould. When the paste stiffened sufficiently for the needle to penetrate only to a point about 5 mm from the bottom, initial set was deemed to have taken place. Initial set was expressed as the time elapsed from the time the mixing water was added to the cement. A minimum time of 45 minutes is prescribed by B.S. 12:1958 for ordinary and rapid hardening portland cements.

Final set was determined by a 1 mm square needle fitted with a metal attachment hollowed out so as to leave a circular cutting edge 5 mm in diameter and set 0.5 mm behind the tip of the needle. Final set is said to have taken place when the needle, gently lowered to the surface of the paste, makes an impression on it but the circular cutting edge fails to do so. The final setting time was reckoned from the moment when mixing water was added to the cement, and is required by the relevant British Standards to be not more than 10 hours for ordinary, rapid hardening, low heat and blast-furnace portland cements. For Ashmoh cement it was of the order of 6 hours.

The setting of cement is affected by the temperature and humidity of the surrounding medium. These are specified

by B.S. 12:1958:temperature between 58 and 64°F (15 and 18°C) and relative humidity of air of not less than 90 per cent.

Speed of setting and rapidity of hardening, i.e. of gain of strength, are entirely independent of one another. For instance, the prescribed setting times of rapid hardening cement are no different from those for ordinary portland cement, although the two cements harden at different rates.

CHAPTER - 5

EXPERIMENTAL RESULTS AND DISCUSSION

In all 157 compositions varying in mixture proportion, water content, curing procedure and additives were tried. Tensile strength data were used for preliminary evaluation and then on selected compositions compressive strength data were obtained.

5.1 Tensile Strength:

5.1.1 Binary Mixtures:

(a) Ashmoh-Rice Husk Ash Mixtures: Ashmoh:rice husk ash mixtures in the ratio 1:1, 1:2 and 1:3 were taken and 6, 5 and 4 levels of water contents were tried respectively. Optimal water content for these mixes were determined for maximum compaction and maximum tensile strength values. The dependence of tensile strength and bulk density on water to cement ratio is plotted in Figure 5.1. Tensile strength and bulk density maxima occur at the same water to cement ratio. Tensile strength values are generally quite low for these bulk densities.

(b) Ashmoh-Sand Mixtures: Ashmoh:sand mixtures in the ratio 1:3, 1:4, 1:5 and 1:6 were taken and 3 water contents for each mix were tried. Optimal water contents

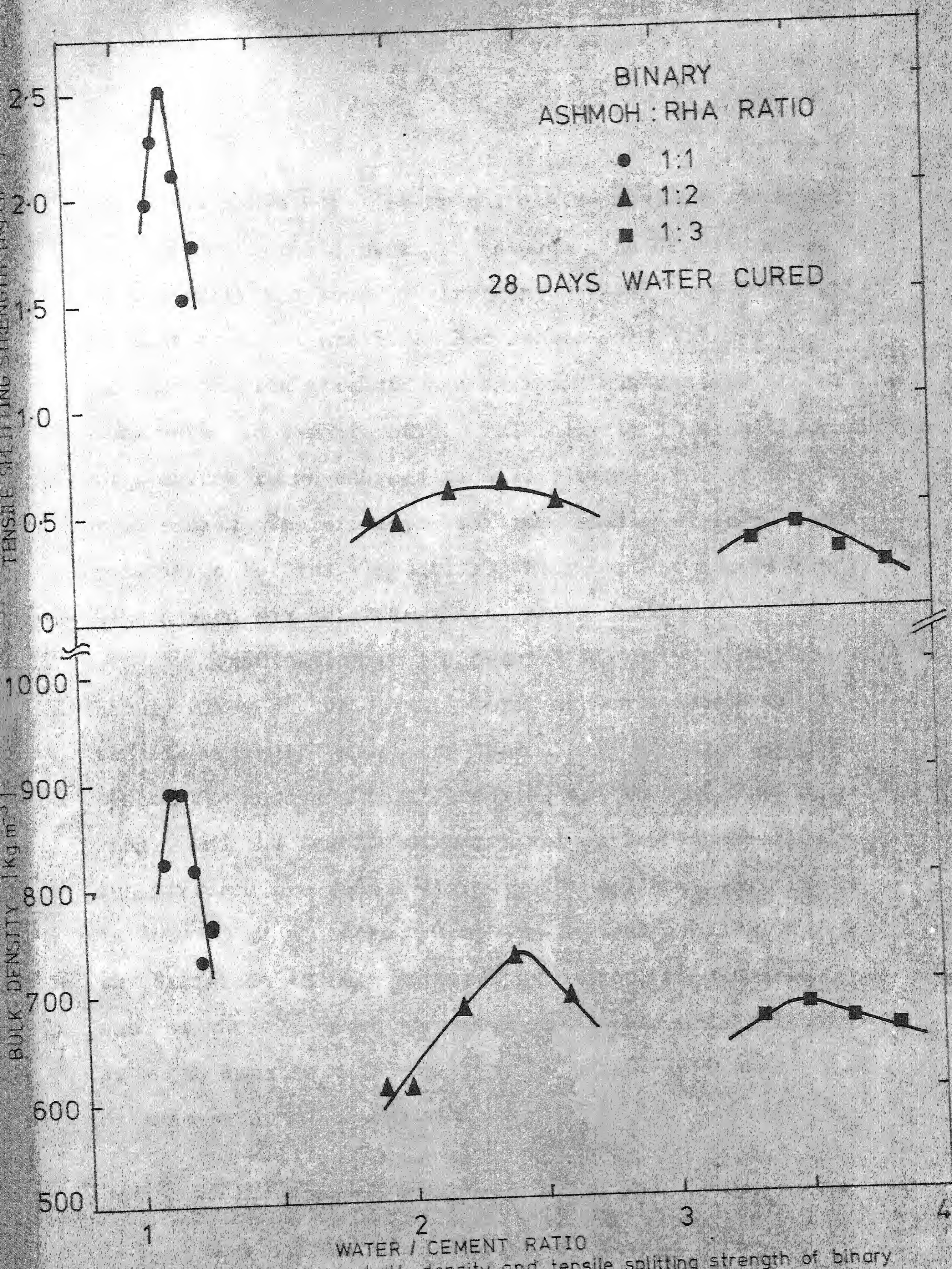


Fig.5·1 Effect of W/C ratio on bulk density and tensile splitting strength of binary mixtures of ASHMOH and rice husk ash.

for these mixes were determined at the maximum compaction and maximum tensile strength values. The dependence of bulk density and tensile strength on water to cement ratio is plotted in Figure 5.2. For Ashmoh:sand 1:3 mix the maximum tensile strength and maximum bulk density are at the same water to cement ratio. Bulk density in general, varies in a narrow range whereas tensile strength varies over a wide range. Therefore the maximum tensile strength was considered to find the optimal water content except for 1:5 Ashmoh:sand mix which does not show a maximum.

Examination of the tensile strength values of binary mixes at the optimal water contents shows that the tensile strength values for Ashmoh:sand mixtures are reasonably good and bulk densities are in 1800-2020 kg/m^3 range, and the tensile strength values for Ashmoh:rice husk ash mixtures are relatively very low and the densities are in 680-900 kg/m^3 range. Thus the logical conclusion was to try different ternary mixtures of Ashmoh, rice husk ash and sand at various water to cement ratios and obtain tensile strength data in mid density range of 900-1800 kg/m^3 at optimal water to cement ratios.

5.1.2 <u>Ternary Mixtures</u>:

(a) <u>Sand Addition in Ashmoh:RHA 1:1 Mixture</u>:

Ashmoh:rice husk ash:sand in 1:1:0.5, 1:1:1.07 and 1:1:2 ratios were taken and four water contents for each mix were

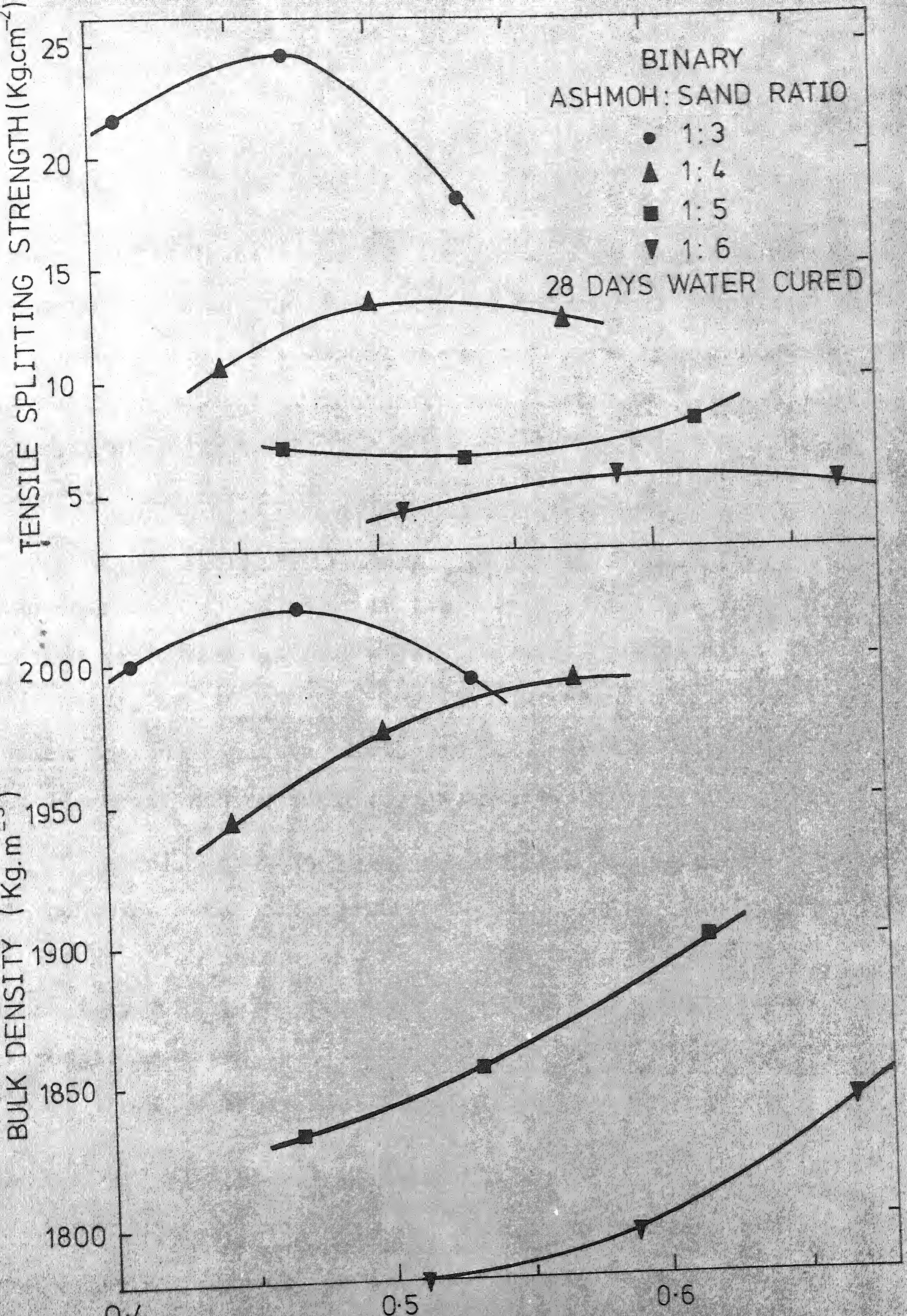


Fig.5·2 EFFECT OF WATER/CEMENT ON BULK DENSITY & TENSILE SPLITTING STRENGTH OF BINARY MIXTURES OF ASHMOH AND SAND.

tried. Optimal water content for these mixes were determined at maximum compaction (bulk density) and maximum tensile strength values. The dependence of bulk density and tensile strength on water to cement ratio is plotted in Figure 5.3. Tensile strength and bulk density maxima occur at the same water to cement ratio.

(b) Sand Addition in Ashmoh:RHA 1:2 Mixture: Ashmoh:rice husk ash:sand in 1:2:0.75; 1:2:1.3 and 1:2:2 ratios were taken at four water contents for each mix. The dependence of bulk density and tensile strength on water to cement ratio is plotted in Figure 5.4. Tensile strength and bulk density maxima occur at the same water to cement ratio.

(c) Sand Addition in Ashmoh:RHA 1:3 Mixture: Ashmoh:rice husk ash:sand in 1:3:1 and 1:3:2.67 ratios were taken at three water contents for each mix. The samples were very weak. The dependence of bulk density and tensile strength on water to cement ratio, plotted in Figure 5.5, shows the same behaviour as before.

5.1.3 Triaxial and Other Plots:

(a) Triaxial Plots: The tensile strength and bulk density data at optimal water to cement ratio obtained in sections 5.1.1 and 5.1.2 were plotted on triangular coordinate paper for the triaxial system of Ashmoh, rice husk ash and sand. Approximate contour lines for bulk

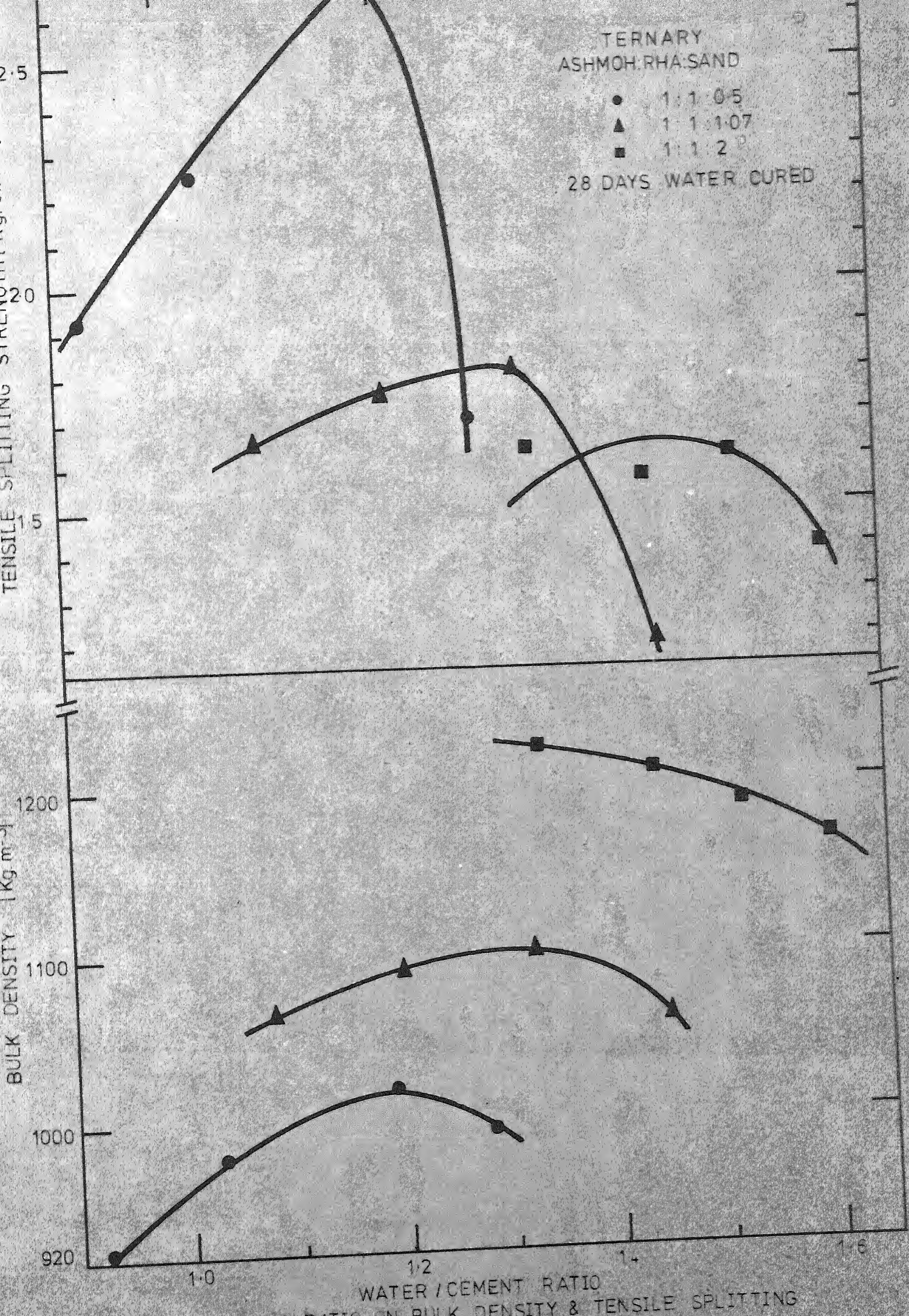


Fig 5.3 EFFECT OF W/C RATIO ON BULK DENSITY & TENSILE SPLITTING STRENGTH OF TERNARY MIXTURES OF ASHMOH:RHA AND SAND

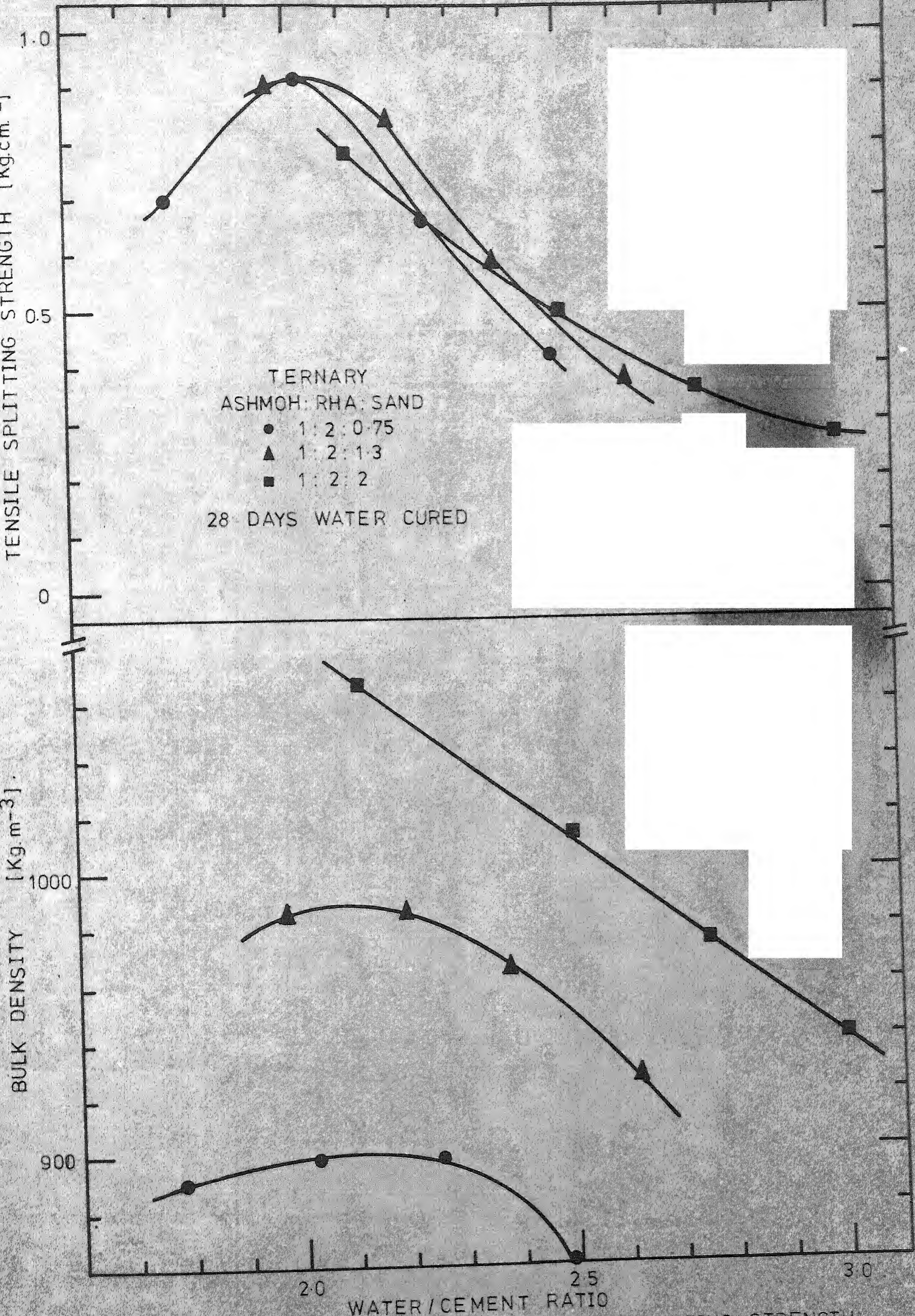


Fig.5·4 EFFECT OF W/C ON BULK DENSITY & TENSILE SPLITTING STRENGTH OF TERNARY MIXTURES OF ASHMOH, RHA AND SAND

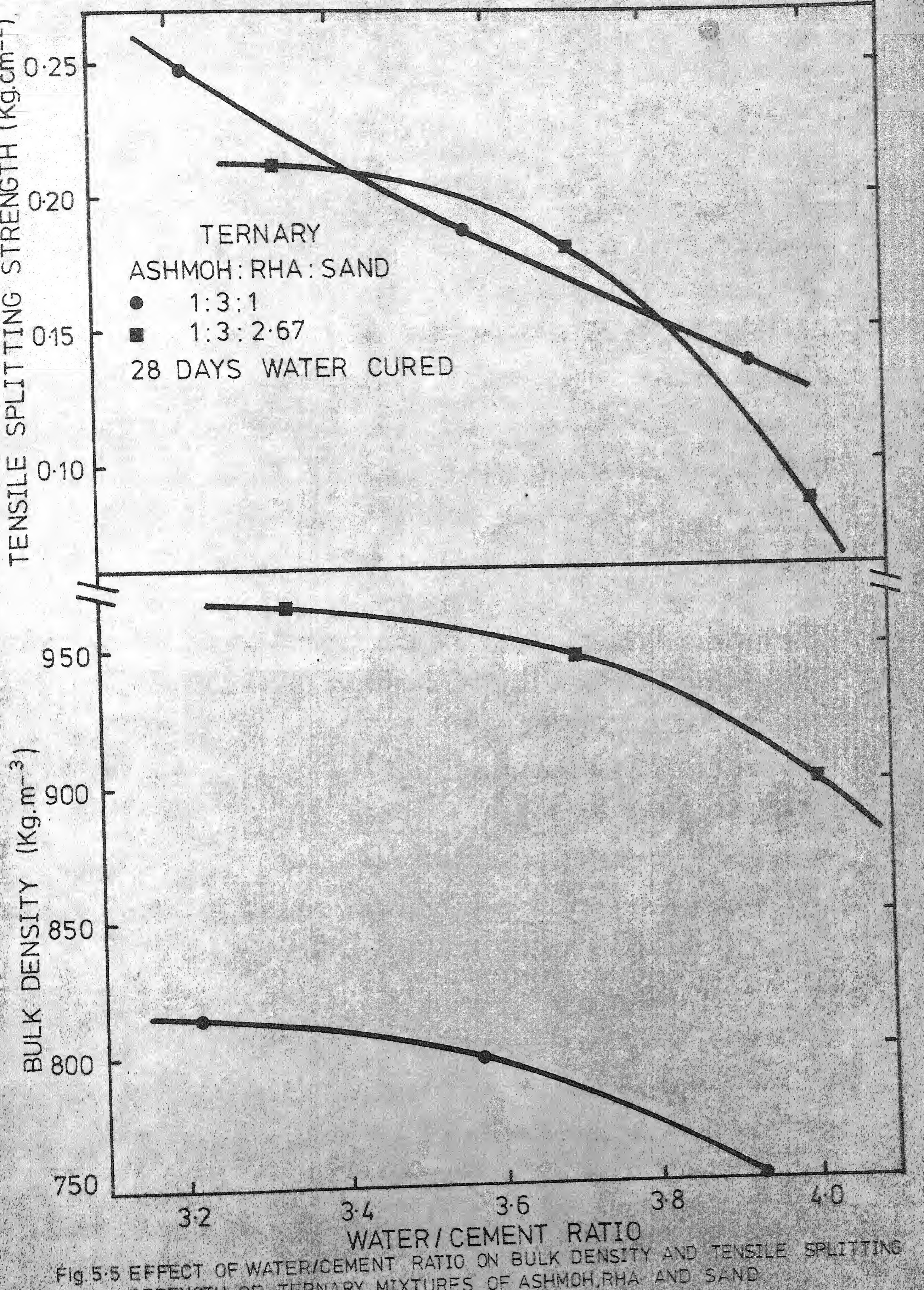


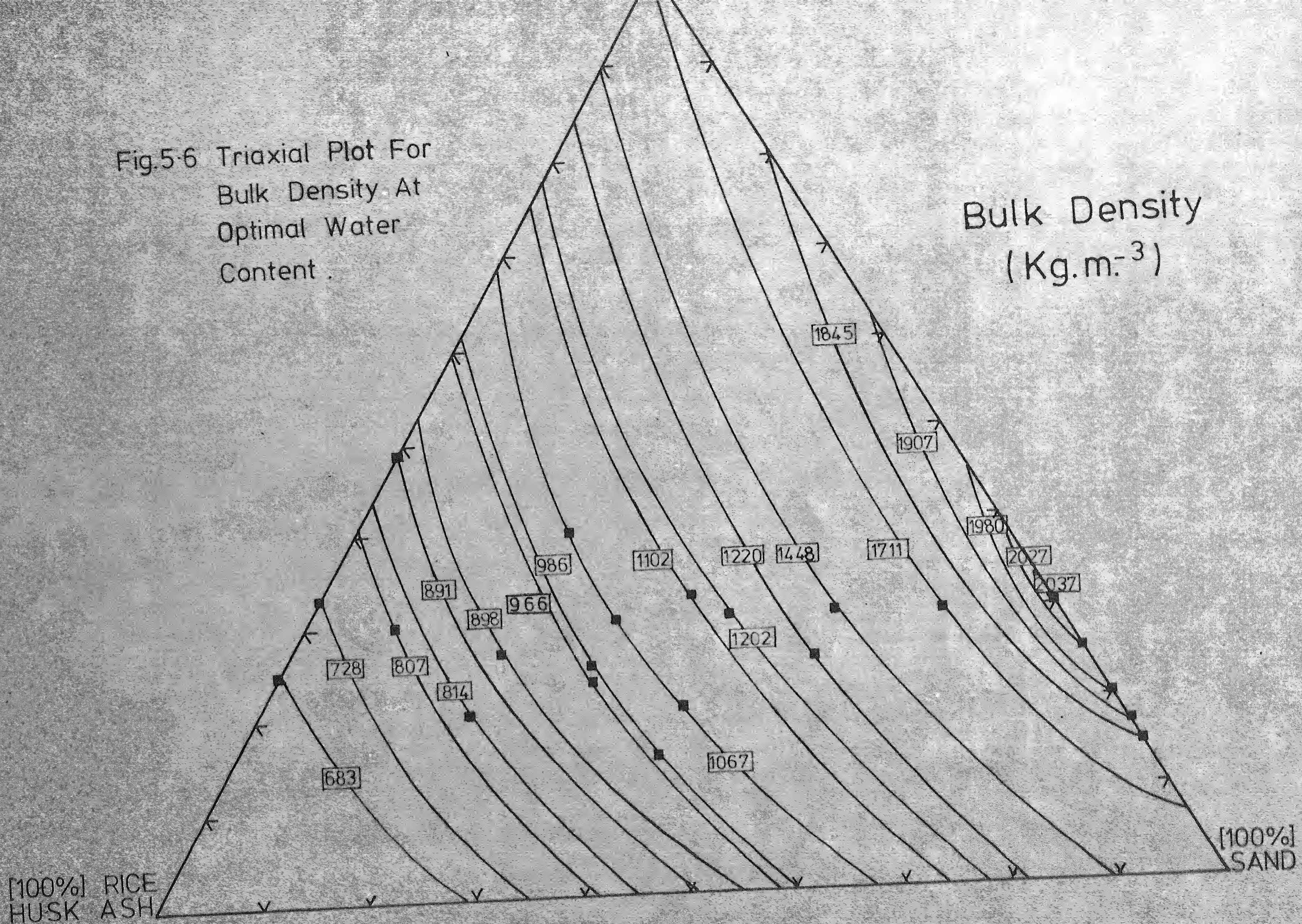
Fig. 5·5 EFFECT OF WATER/CEMENT RATIO ON BULK DENSITY AND TENSILE SPLITTING STRENGTH OF TERNARY MIXTURES OF ASHMOH, RHA AND SAND

density, tensile strength and tensile strength to bulk density ratio are shown in Figures 5.6, 5.7 and 5.8 respectively. Corners of the triangle indicate 100% Ashmoh, rice husk ash and sand. These plots give us information about bulk density, tensile strength and tensile strength to bulk density ratio when any ternary mixture with these three components at optimal water to cement ratio is taken and also we can find the range of ternary mixture compositions having some bulk density, tensile strength and tensile strength to bulk density ratio level.

(b) Bulk Density, Tensile Strength and Optimal Water to Cement Ratio vs. Aggregate Composition Plots at Various Ashmoh Levels: From the triaxial plots, at Ashmoh levels most commonly used (20, 25 and 30% by wt. of mix) bulk density; tensile strength and optimal water to cement ratio vs. aggregate composition (% sand or % RHA in aggregate mixture of sand and RHA) were plotted, as shown in Figure 5.9. These plots readily give us the information on optimal water to cement ratio (also on bulk density and tensile strength) when any aggregate composition of sand, rice husk ash is taken at these three Ashmoh cement levels, and were very helpful in the later part of our work.

(c) Master Plots: From the data so far, we would also like to know the tensile strength of a mix

Fig.5·6 Triaxial Plot For Bulk Density At Optimal Water Content.



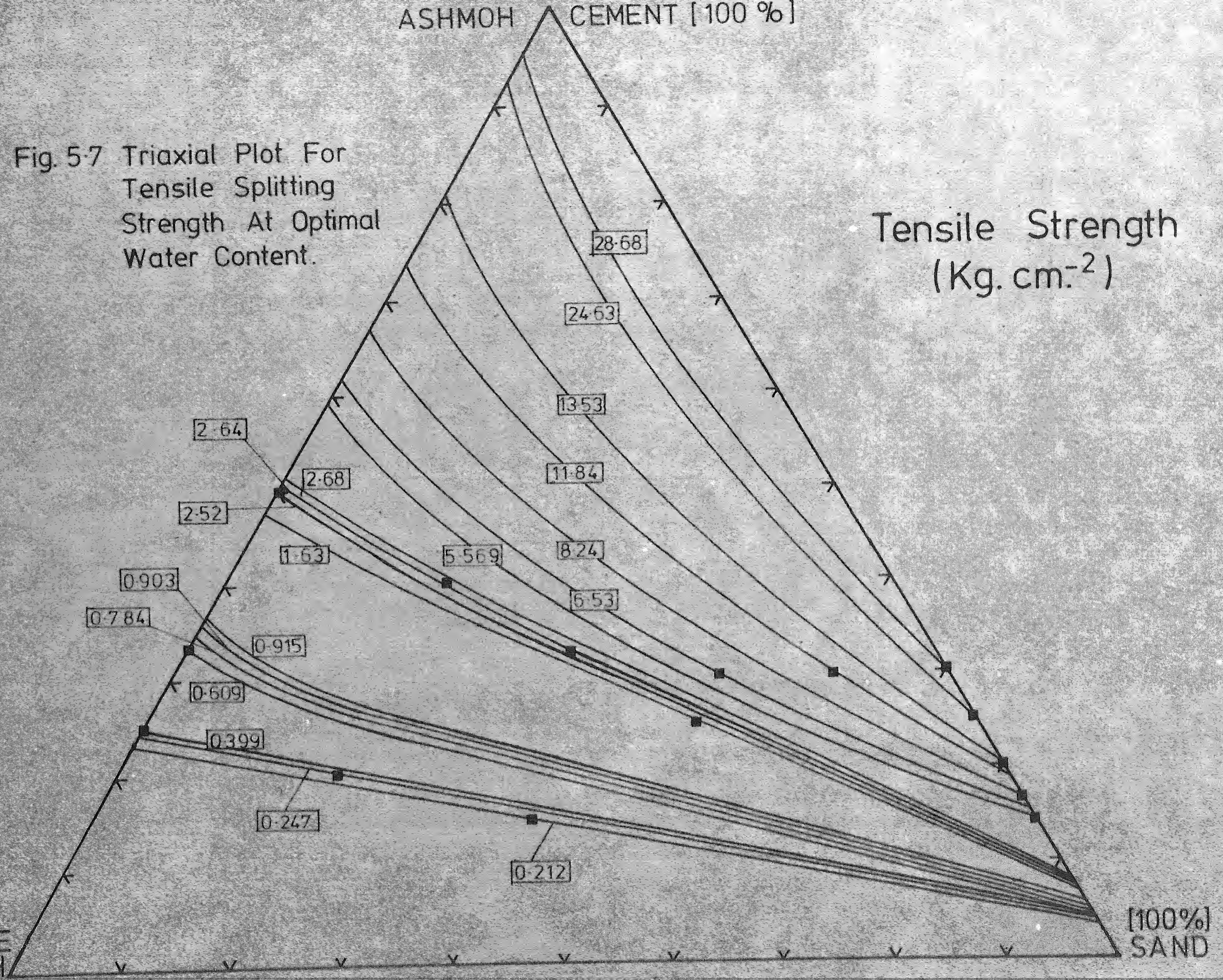


Fig. 5·7 Triaxial Plot For Tensile Splitting Strength At Optimal Water Content.

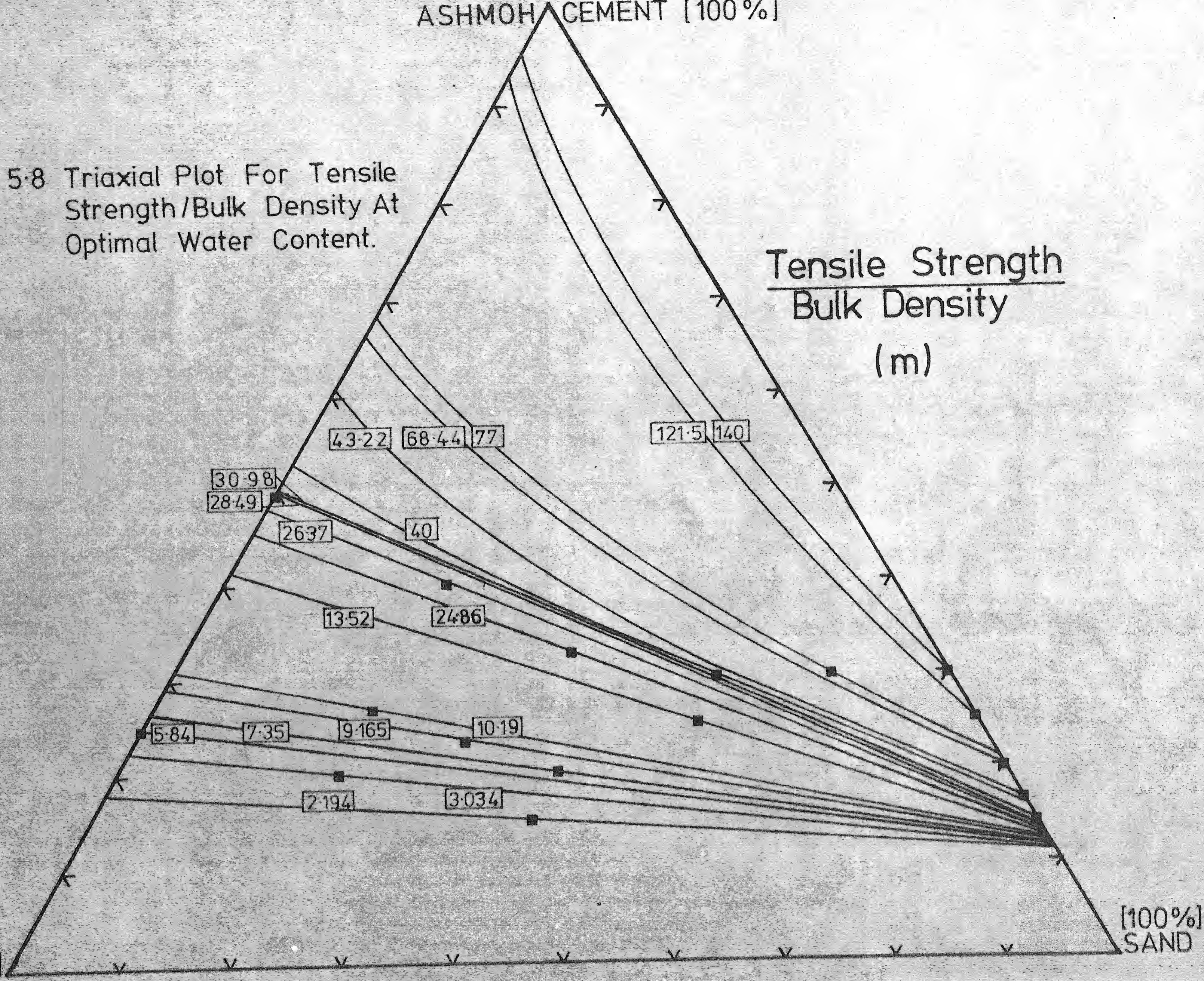


Fig. 5·8 Triaxial Plot For Tensile Strength/Bulk Density At Optimal Water Content.

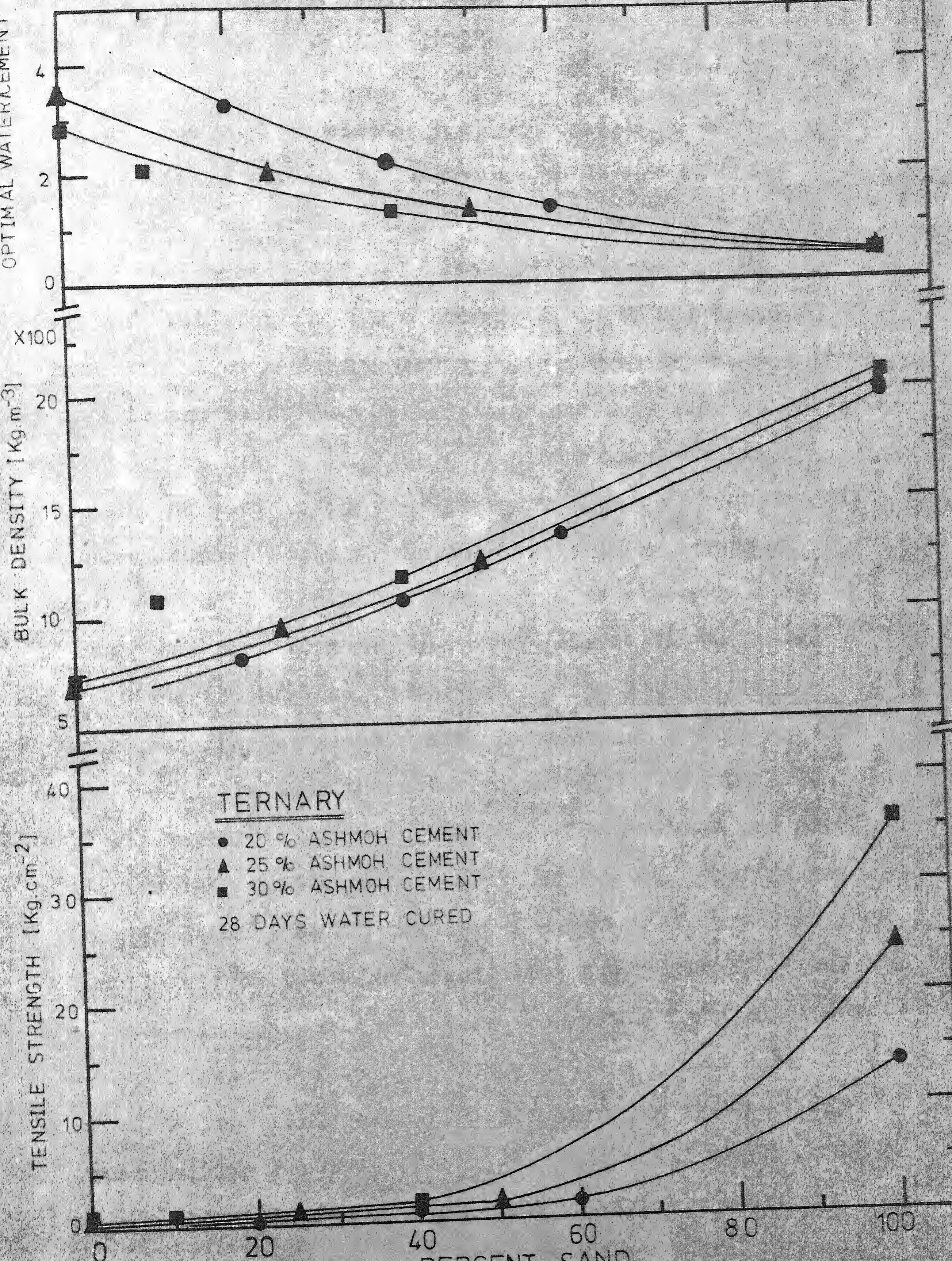


Fig.5.9 Max. Tensile Strength, Bulk Density and Optimal W/C variation with Aggregate Composition at various Ashmoh Cement Levels.

against the cost of the mix i.e. how cheaply or expensively we can attain various tensile strength levels at their respective densities. Ashmoh being the costliest of the three components of the mix can easily be used as an index of the cost of mix. Hence tensile strength and tensile strength to bulk density ratio vs. per cent Ashmoh cement in the mix are plotted in Figures 5.10 and 5.11 respectively.

In Figure 5.10 the curve for binary mixture of Ashmoh and sand is the most steep one (lies close to y-axis) i.e. as Ashmoh content increases the tensile strength increases at a high rate. The curve for binary mixture of Ashmoh and rice husk ash when extrapolated is the least steep one (lies close to x-axis) i.e. as Ashmoh content increases the tensile strength increases at a very low rate. The area in between these two curves represents the field of all ternary mixtures of Ashmoh, rice husk ash and sand All the Ashmoh rich ternary mixtures lie away from x-axis. In rich Ashmoh-RHA mixtures small addition of sand increases tensile strength but large additions lower tensile strength values. In weak or lean Ashmoh-RHA mixtures any addition of sand lowers the tensile strength. Any vertical line starting from Ashmoh-sand binary and ending at Ashmoh-RHA binary will represent a mix of constant total aggregate by weight (constant Ashmoh level) but of variable aggregate composition, sand at one binary end and rice husk ash on another binary end.

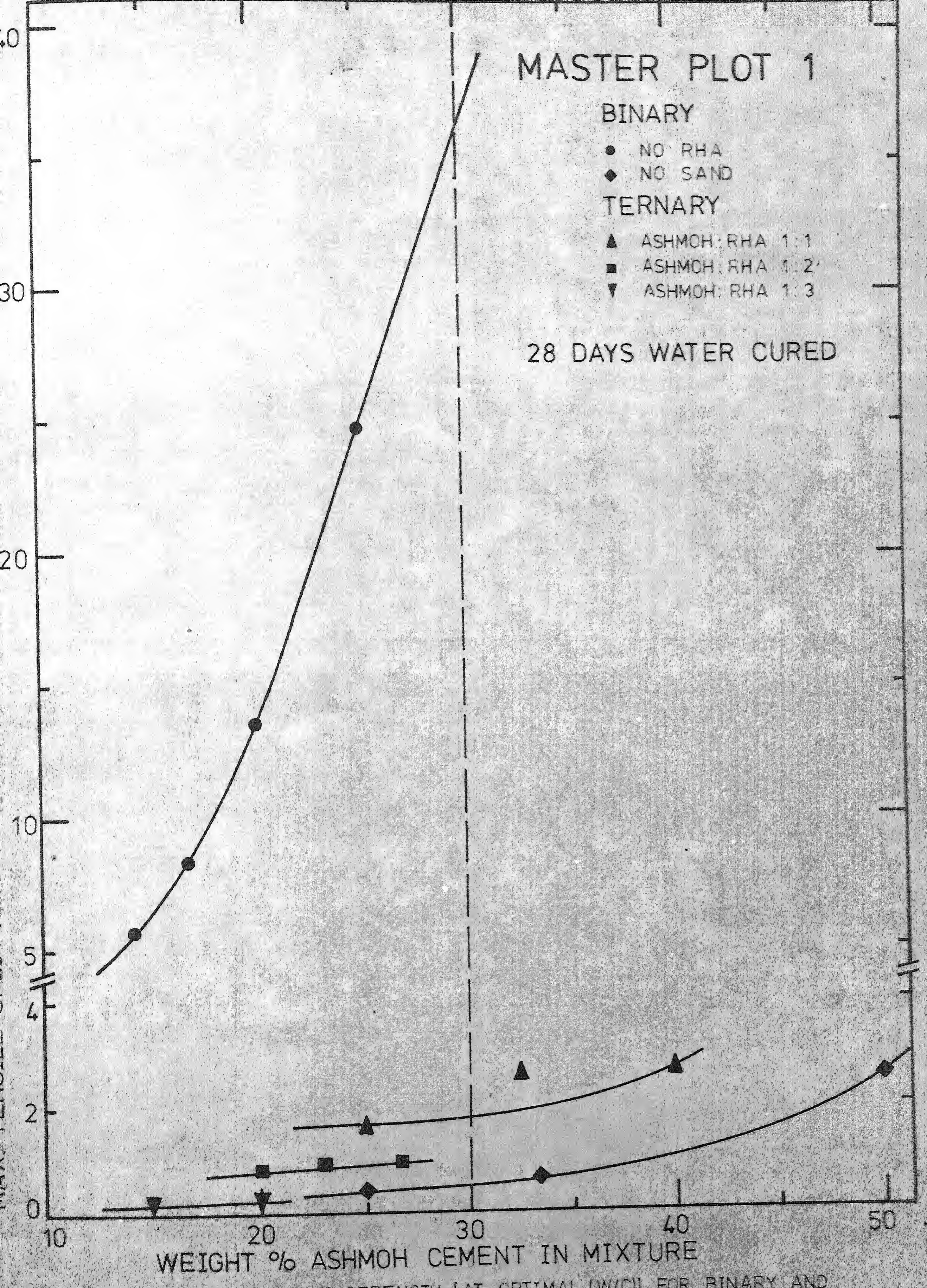


Fig. 5.10 MAXIMUM TENSILE STRENGTH [AT OPTIMAL (W/C)] FOR BINARY AND TERNARY MIXTURES AT VARIOUS ASHMOH CEMENT LEVELS.

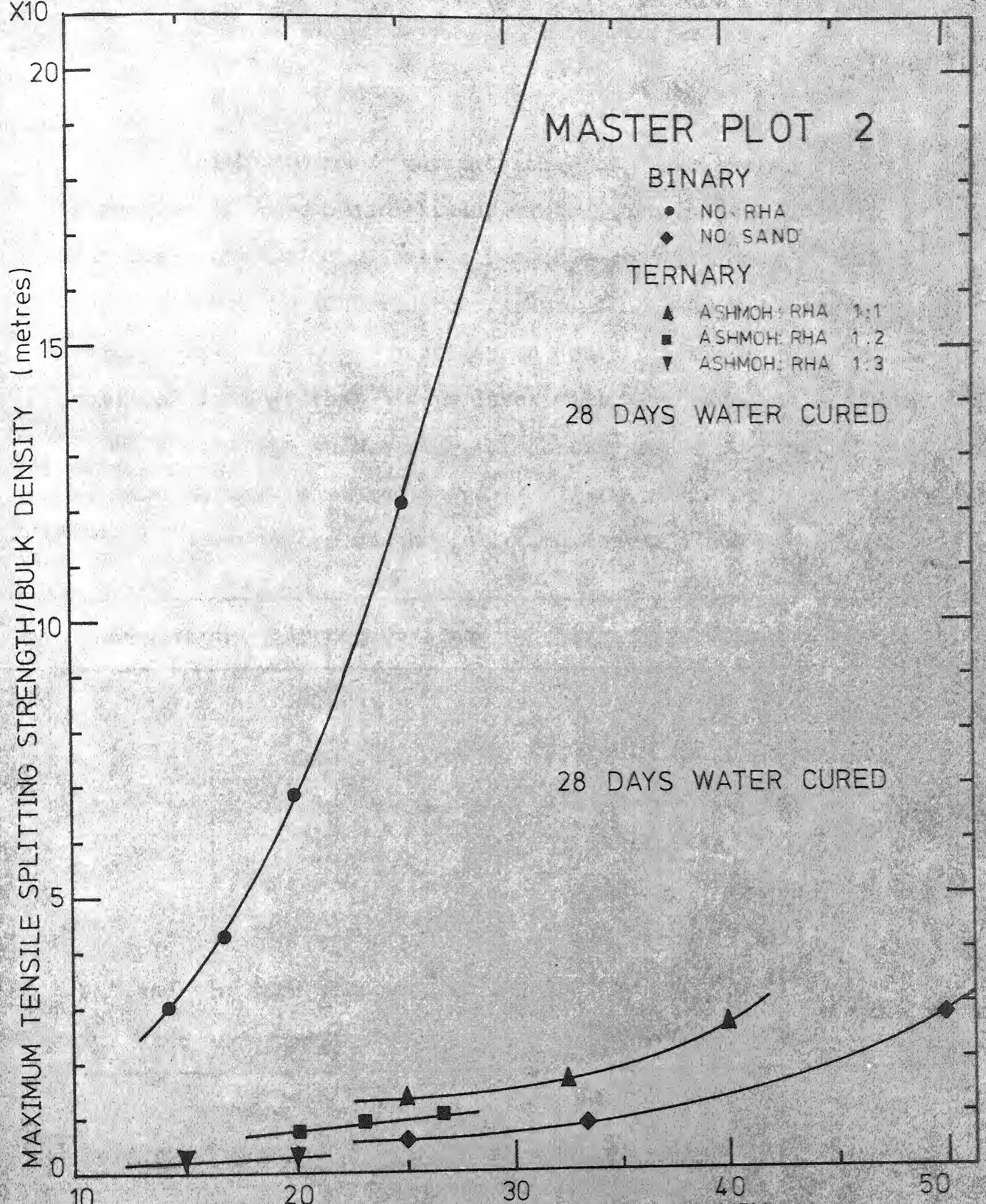


Fig. 5.11 MAXIMUM TENSILE STRENGTH/BULK DENSITY [AT OPTIMAL(W/C)] FOR BINARY AND TERNARY MIXTURES AT VARIOUS ASHMOH CEMENT LEVELS.

With a further careful study of Figure 5.10, the steepness of Ashmoh-sand binary mixture can be exploited to get reasonably good tensile strength values at lower density levels. This is achieved by extrapolating Ashmoh-sand binary curve to 30 per cent Ashmoh cement level and a vertical line at that cement level will give reasonably good tensile strength values over the density range of nearly all the ternary mixtures there.

Thus we choose the following compositions:

Composition	Ashmoh content	Aggregate composition
C1	30	70 (70 Sand, 0 RHA)
C2	30	70 (59.5 Sand, 10.5 RHA)
C3	30	70 (49 Sand, 21 RHA)
C4	30	70 (38.5 Sand, 31.5 RHA)
C5	30	70 (28 Sand, 42 RHA)
C6	30	70 (7 Sand, 63 RHA)
and one standard composition		Ashmoh:Sand = 1:3 i.e.
C7	25	75 (75 Sand, 0 RHA)

5.2 Tensile Strength and Compressive Strength:

Effect of curing procedures and tensile strength to compressive strength ratio: The optimal water to cement ratios for compositions C1 to C7 were found from Figure 5.9.

Both tensile and compressive strengths were determined after 28 days water curing and 5 hours steam (1 atm) curing. The results are plotted in Figures 5.12, 5.13 and 5.14.

A plot of 28 days water cured compressive strength vs. bulk density is made again in Figure 5.15 alongwith the specifications of compressive strength values (in the band form) over the bulk density range in order to compare our products with the standard band at various density levels.

Compositions C1, C2 and C7 lie above or within the band hence they are acceptable. Of the remaining four compositions which fall below the specified band we chose two representative compositions namely HEAVY (C3) and LIGHT (C6) for upgrading. These were abbreviated HC3 and LC6 and only compressive strength study was carried out.

5.3 Compressive Strength:

5.3.1 Upgrading of Heavy (HC3) and Light (LC6):

For upgrading Heavy (HC3) and Light (LC6) compositions portland cement was used as partial substitute to Ashmoh cement or added extra as some percentage of the total mix.

On Heavy (HC3) four replacements of Ashmoh by portland cement (25, 50, 75, 100%) were tried. Two additions of portland cement 10, 25% by weight of the total mix were also tried. Effect of replacement is shown in

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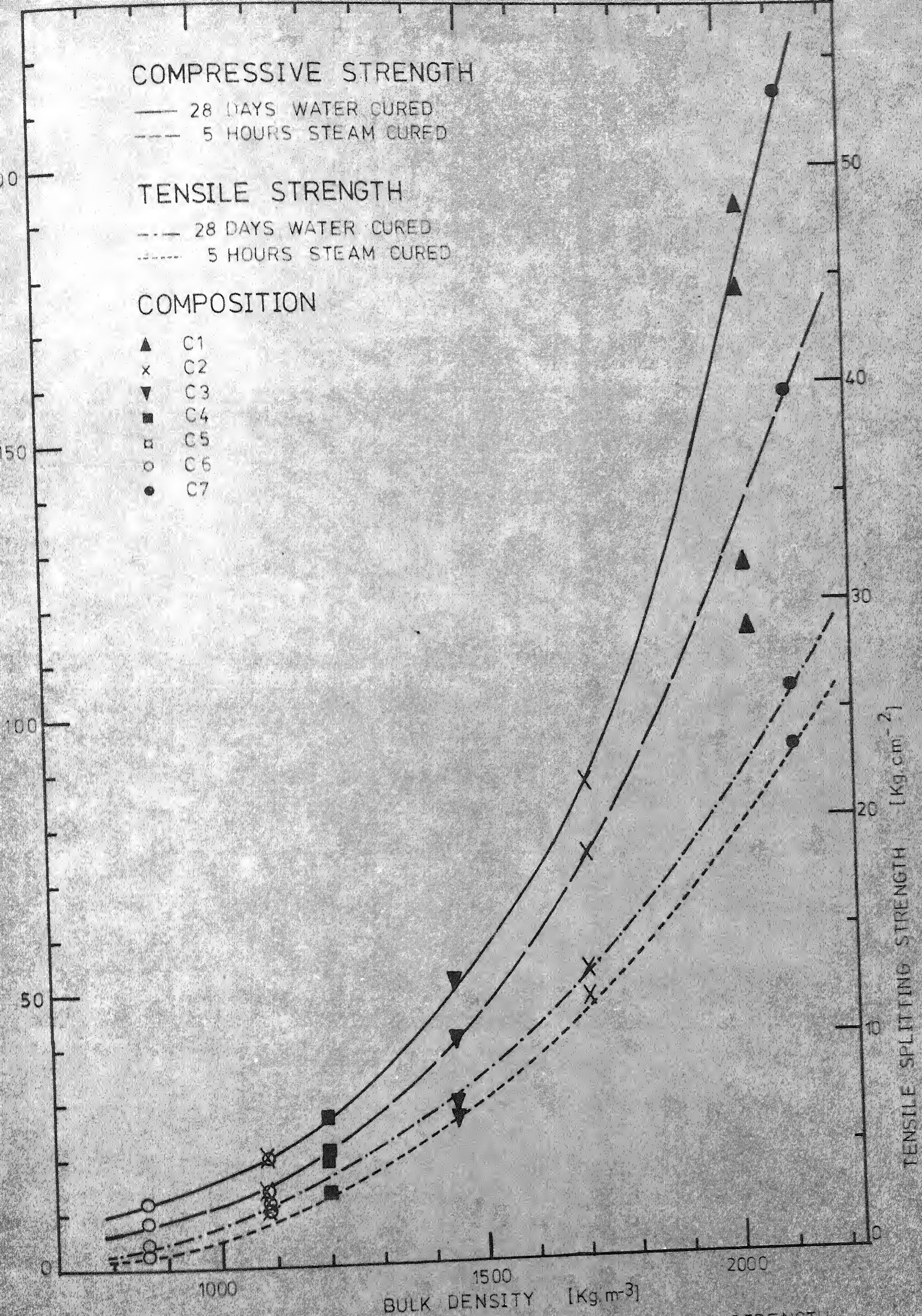


Fig 5.12 VARIATION OF COMPRESSIVE STRENGTH AND TENSILE STRENGTH WITH BULK DENSITY

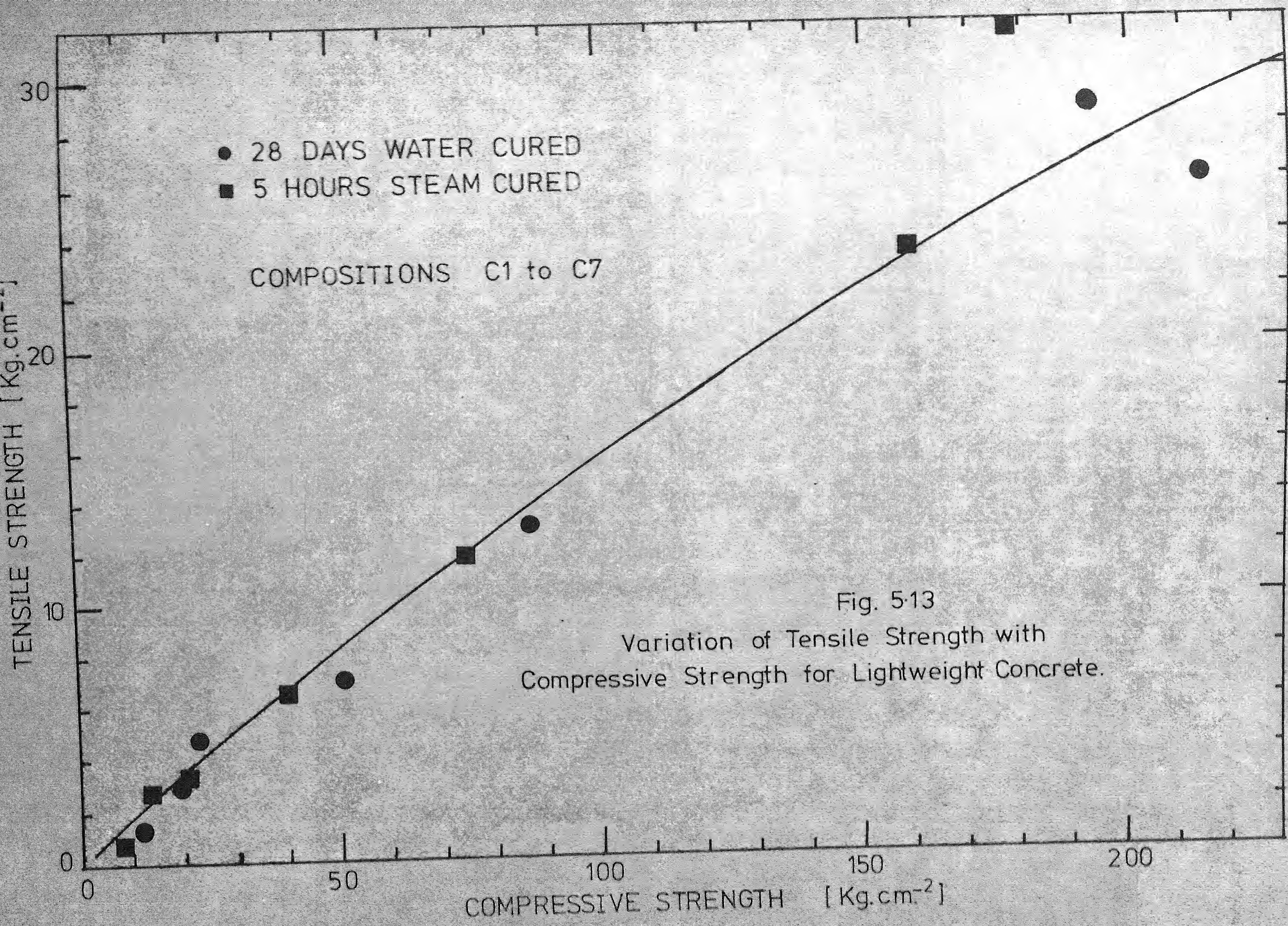


Fig. 5·13
Variation of Tensile Strength with Compressive Strength for Lightweight Concrete.

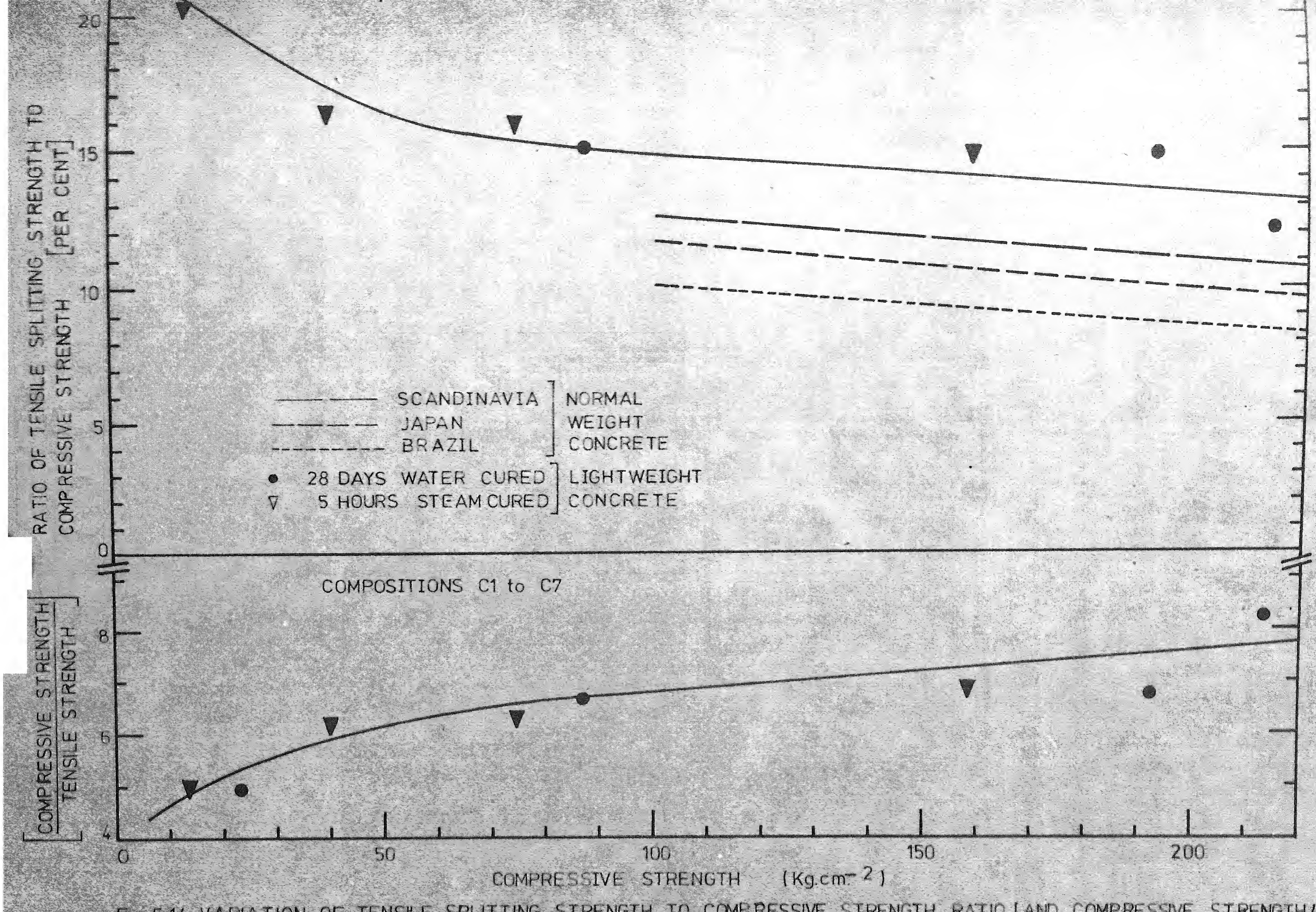


Fig. 5.14 VARIATION OF TENSILE SPLITTING STRENGTH TO COMPRESSIVE STRENGTH RATIO [AND COMPRESSIVE STRENGTH/ TENSILE STRENGTH] WITH COMPRESSIVE STRENGTH FOR LIGHTWEIGHT CONCRETE.

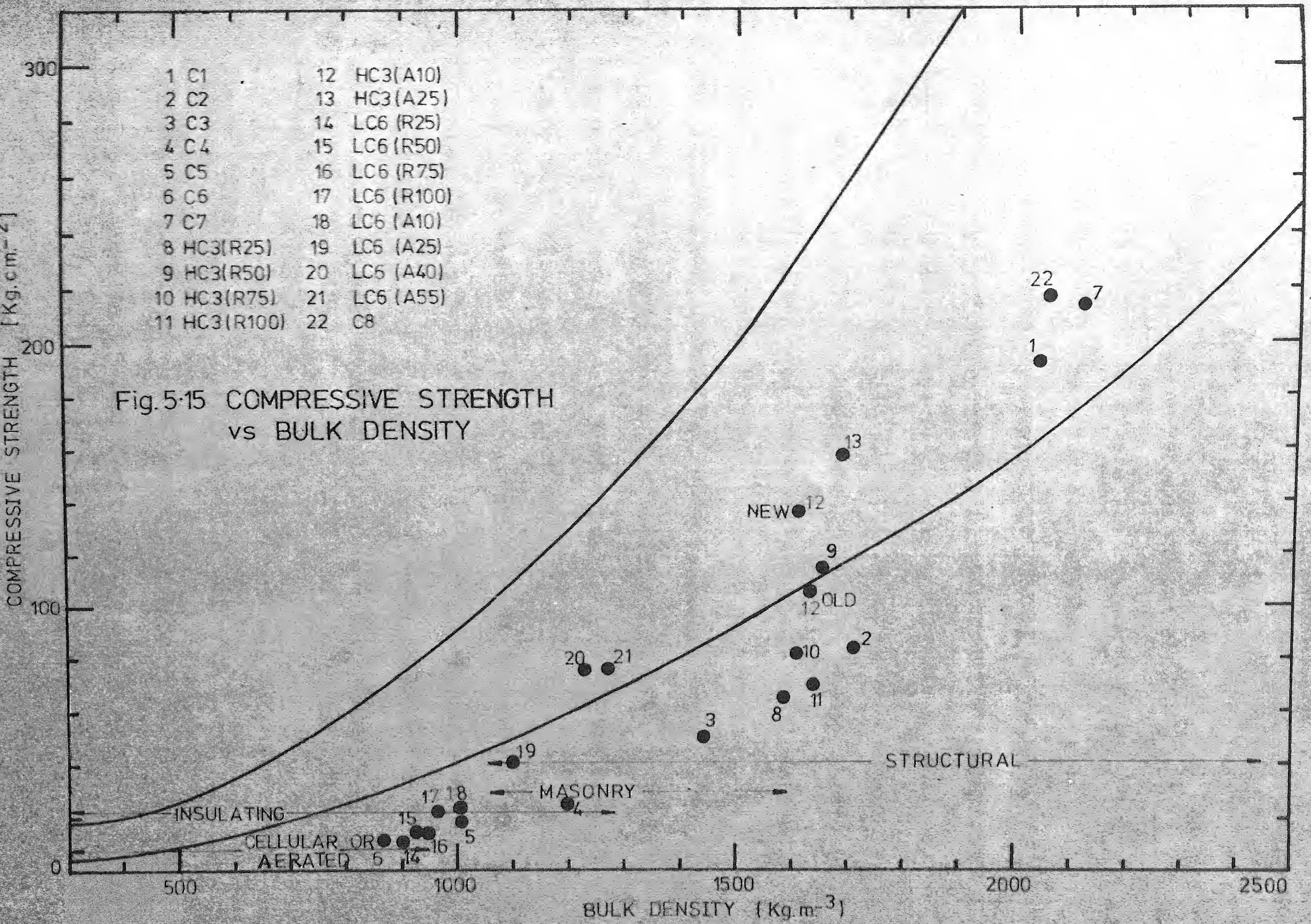


Fig. 5·15 COMPRESSIVE STRENGTH vs BULK DENSITY

Figure 5.16. Bulk density remains almost constant but compressive strength and compressive strength to bulk density ratio have maxima at 50% replacement. Also we note a significant increase in strength by replacing Ashmoh by portland cement, especially at 50% replacement the compressive strength value is sufficiently high to put this composition in the band in Figure 5.15. Effect of portland cement added extra in HC3 is shown in Figure 5.17. Bulk density increases slightly; both compressive strength and compressive strength to bulk density ratio increase significantly by addition of portland cement. Both additions of portland cement 10, 25% by weight of the total charge give good compressive strength values which again fall in the band in Figure 5.15 at respective densities.

In Light LC6 composition as portland cement is substituted in place of 25, 50, 75 and 100% Ashmoh (by weight) the compressive strength and bulk density increase is not significant. This is shown in Figure 5.16. The effect of portland cement added extra in LC6 is shown in Figure 5.17. All additions (10, 25, 40 and 55%) increase the compressive strength and bulk density. Only 40% addition is of importance as it increases the compressive strength to band level in Figure 5.15. Any further addition of portland cement does not help as compressive strength levels off and bulk density increases hence compressive strength to bulk density ratio decreases.

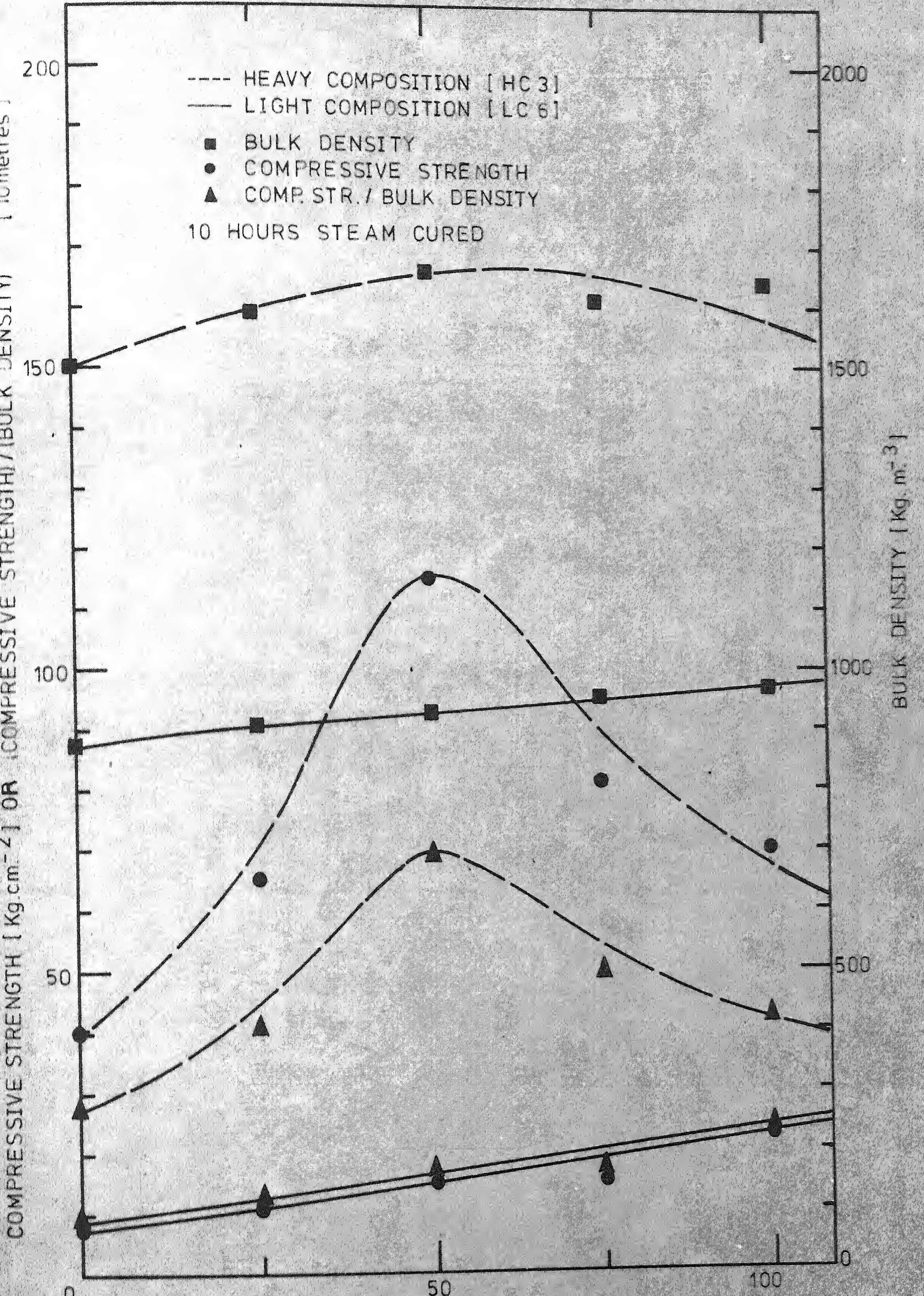


Fig.5.16 Effect of replacing Ashmoh by Portland Cement.

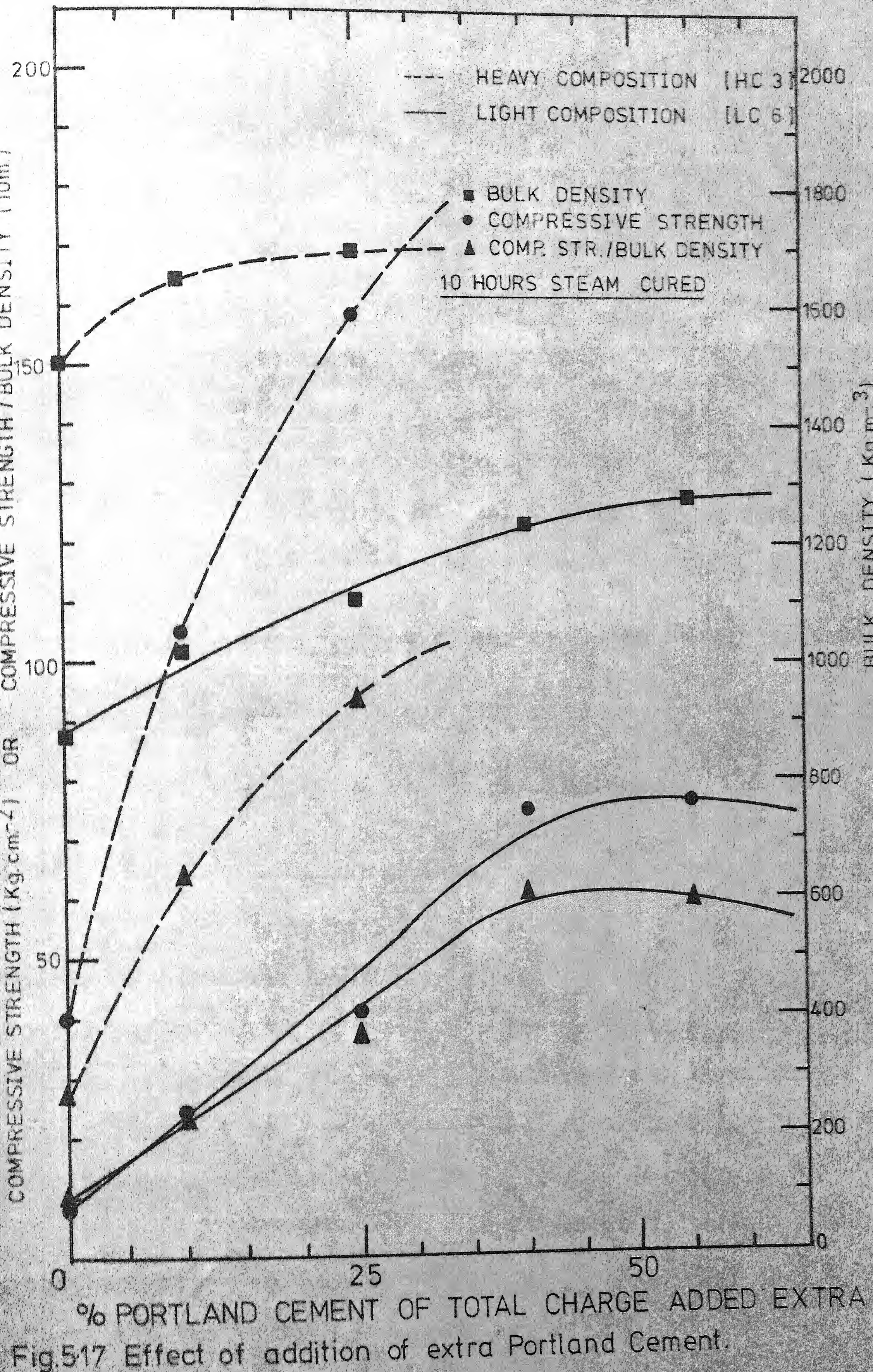


Fig.5·17 Effect of addition of extra Portland Cement.

5.3.2 Final Compositions:

From section 5.2 and 5.3.1 we have the following final compositions which meet the lightweight concrete requirements.

C1	(30 Ashmoh, 0 RHA, 70 Sand)
C2	(30 Ashmoh, 10.5 RHA, 59.5 Sand)
C7	(25 Ashmoh, 0 RHA, 75 Sand)
HC3 (R50)	(15 Ashmoh, 21 RHA, 49 Sand, 15 portland cement)
HC3 (A10)	(HC3 + 10% portland cement by weight of total mix HC3)
HC3 (A25)	(HC3 + 25% portland cement by weight of total mix HC3)
LC6 (A40)	(LC6 + 40% portland cement by weight of total mix LC6)
C8	(22.2 Ashmoh, 0 RHA, 77.8 Sand)

5.3.3 Steam Curing Time Effect:

While upgrading HC3 in section 5.3.1 ten extra cubes of composition HC3 (A10) were made and were steam-cured for 0, 5, 10, 15 and 20 hours. The steaming time effect is shown in Figure 5.18. Steaming for more than 10 hours does not help as the compressive strength levels off for steaming time greater than 10 hours. Steaming for 10 hours gives compressive strength values equal to that obtained after 28 days water curing. Hence, after this study all the samples i.e. cubes or pellets (including

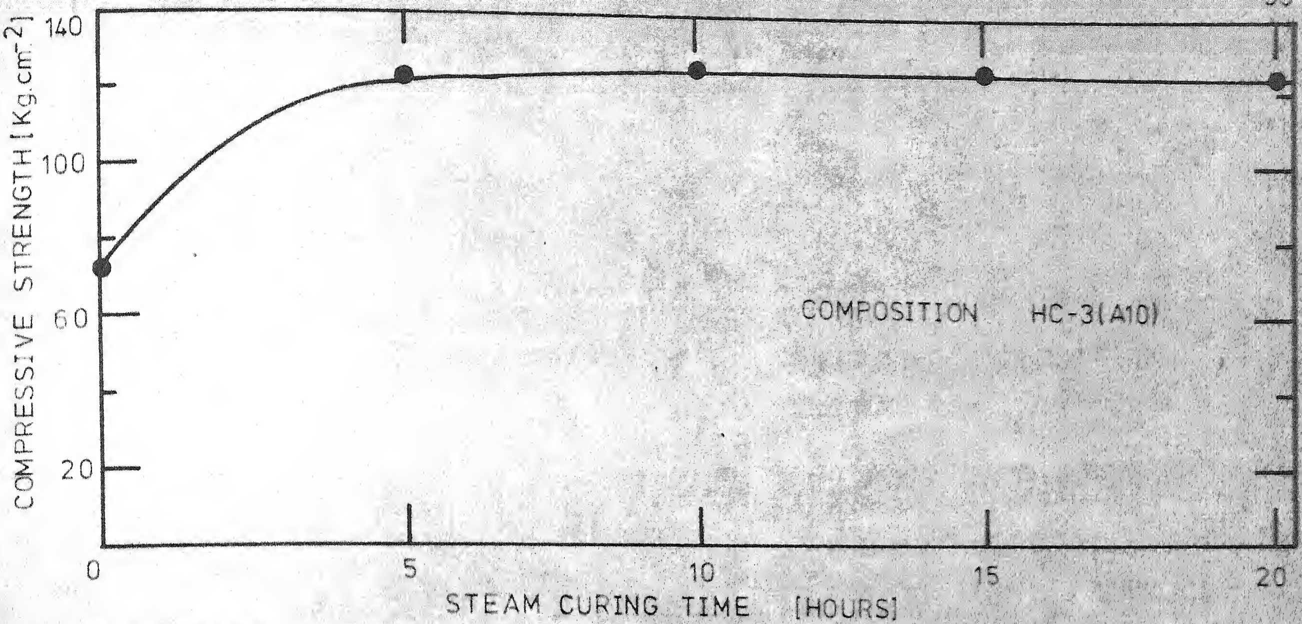
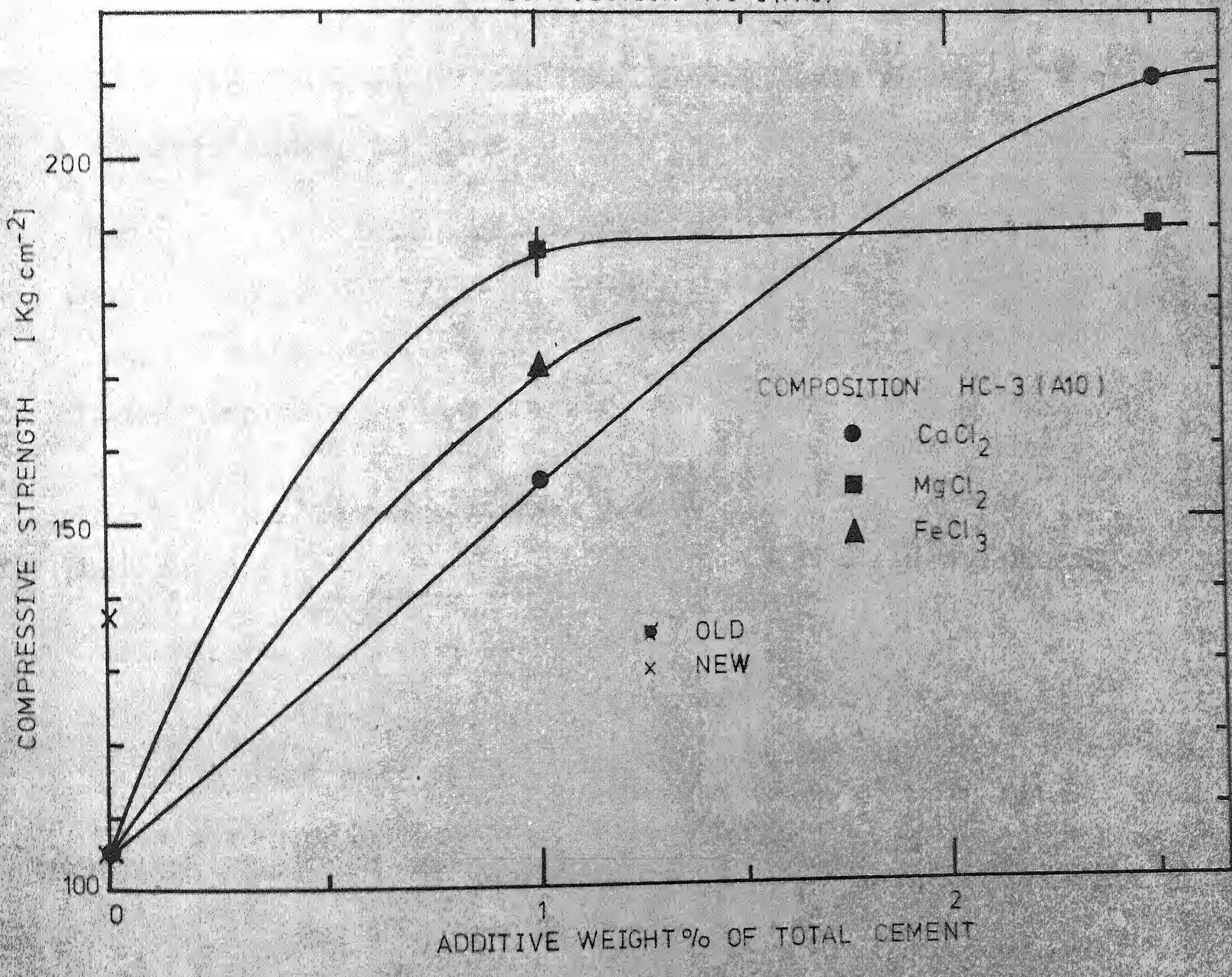


Fig. 5·18 EFFECT OF STEAM CURING ON THE COMPRESSIVE STRENGTH OF LIGHTWEIGHT COMPOSITION.

Fig 5·19 EFFECT OF ADDITIVES ON COMPRESSIVE STRENGTH OF LIGHTWEIGHT COMPOSITION HC-3(A10)



those in section 5.3.1) were steam cured for 10 hours to get an estimate of 28 days water cured compressive strength and to get results faster.

5.3.4 Effect of Additives:

(a) On Heavy Composition HC3 (A10): $CaCl_2$, $MgCl_2$ and $FeCl_3$ additives were used 1, 2.5% by weight of total cement in composition HC3 (A10). Compressive strength is increased considerably as can be seen in Figure 5.19. $CaCl_2$ is the most effective additive followed by $MgCl_2$ and $FeCl_3$. An optimum amount of additive, 2-2.5% by weight of total cement, should be used.

(b) On Light Composition LC6: The same additives used above were tried on composition LC6 in the above-mentioned manner. Additives did not work for this composition and decreased the compressive strength values.

5.3.5 Miscellaneous Compositions:

(a) Ashmoh-Sand Mortar Cubes: Ashmoh:sand 1:3 mortar cubes with water to cement ratio 0.5 (higher water content; optimal W/C 0.47) were made and tested for 7, 14 and 28 days water cured compressive strengths. The compressive strengths are plotted in Figure 5.20.

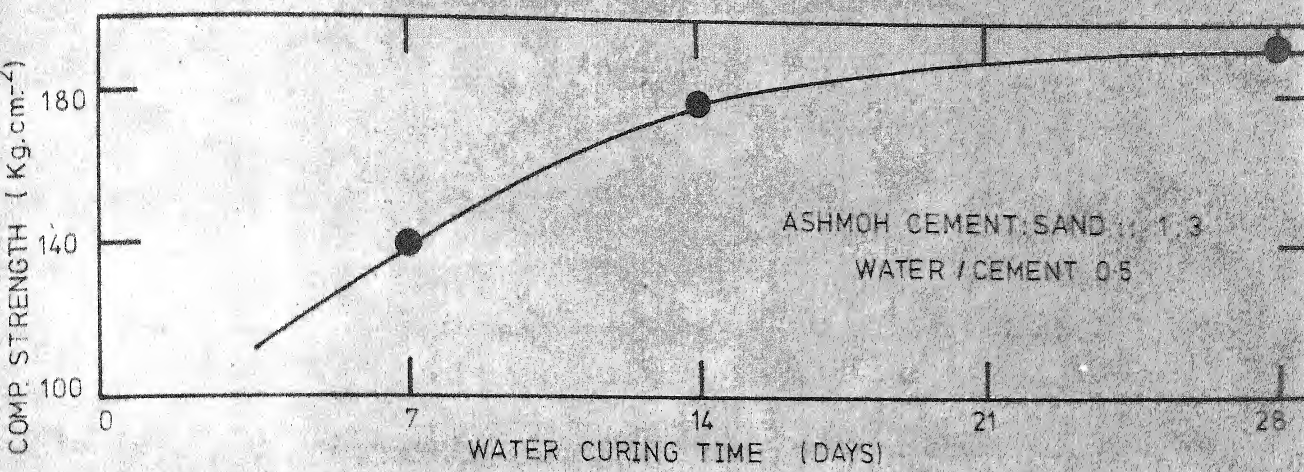
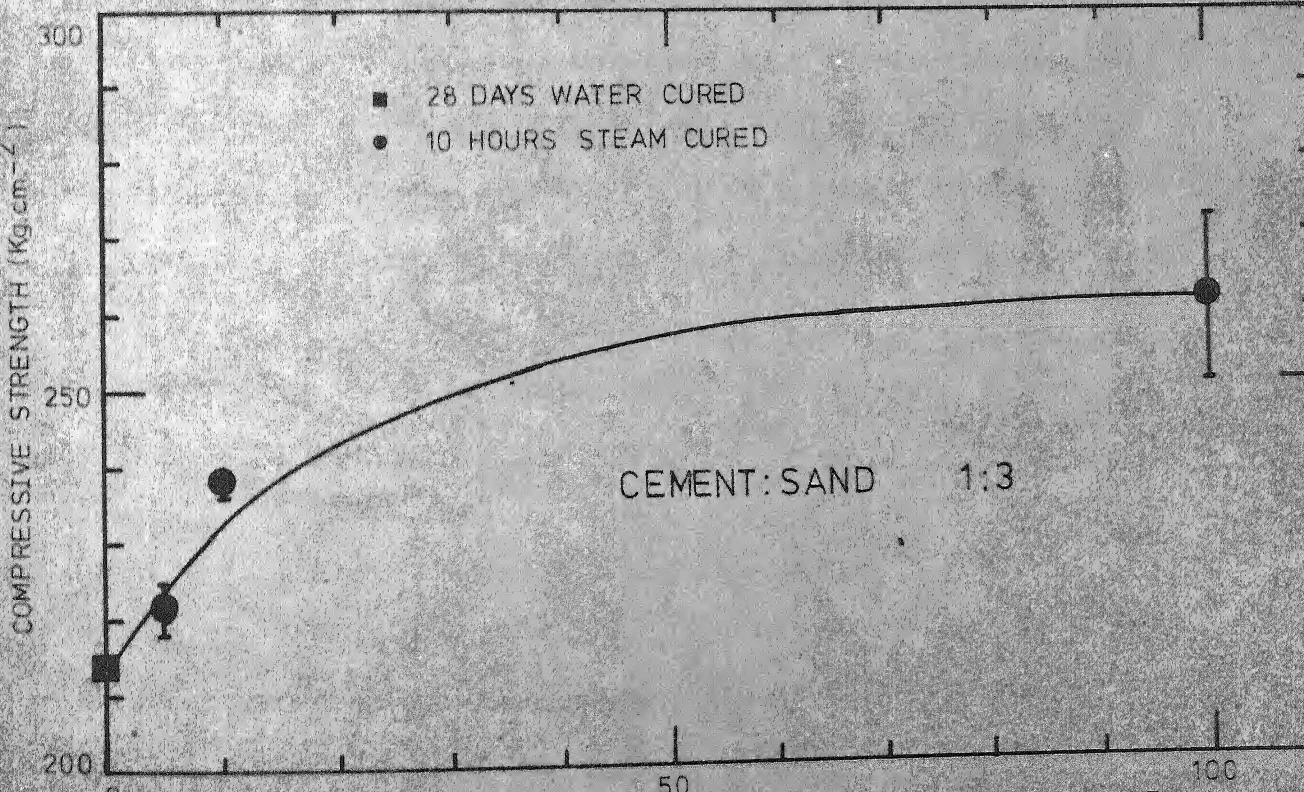


Fig.5·20 EFFECT OF WATER CURING ON COMPRESSIVE STENGTH OF ASHMOH-SAND (1:3) MORTAR CUBES.

Fig.5·21 EFFECT OF REPLACEMENT OF ASHMOH CEMENT BY PORTLAND CEMENT ON COMPRESSIVE STRENGTH.



(b) Effect of Replacement of Ashmoh by Portland Cement on Ashmoh:Sand 1:3 Mortar Mixtures: 5, 10 and 100% Ashmoh was replaced by portland cement and cement:sand 1:3 mortar cubes were steam-cured for 10 hours and compressive strengths were measured. The results are plotted in Figure 5.21 showing increase in compressive strength as portland cement content increases.

(c) Upgrading of Composition C6: Composition C6 was upgraded by adding extra portland cement 8, 16 and 25% by weight of total mix C6, and by adding 2.5% $CaCl_2$ by weight of total cement. The samples were steam-cured for 10 hours and were tested for compressive strength. The compressive strength values were increased significantly, however they could not reach the band to meet the required specifications. The effect of upgrading on bulk density, compressive strength and water absorption is shown in Figure 5.22.

5.3.6 Standard Samples:

Six cubes each of 5 standard compositions C7, HC3 (A10), HC3 (A25), LC6 (A40) and C8 were made. Two cubes of each were tested for compressive strength and one for water absorption. The results are plotted in Figure 5.23. All the compositions meet the compressive strength requirements of Figure 5.15.

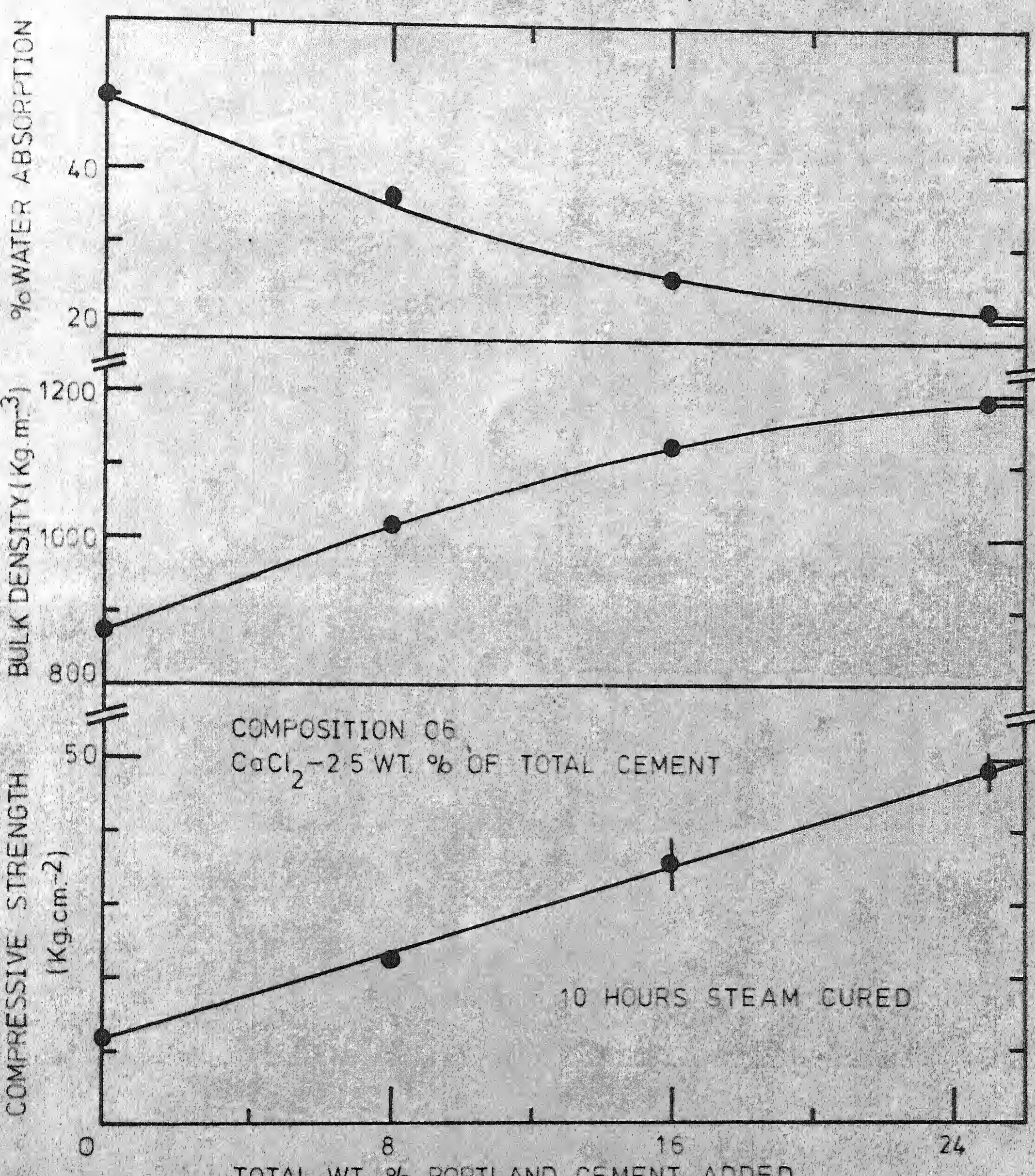


Fig. 5·22 UPGRADING OF COMPOSITION C6 BY ADDITION OF PORTLAND CEMENT.

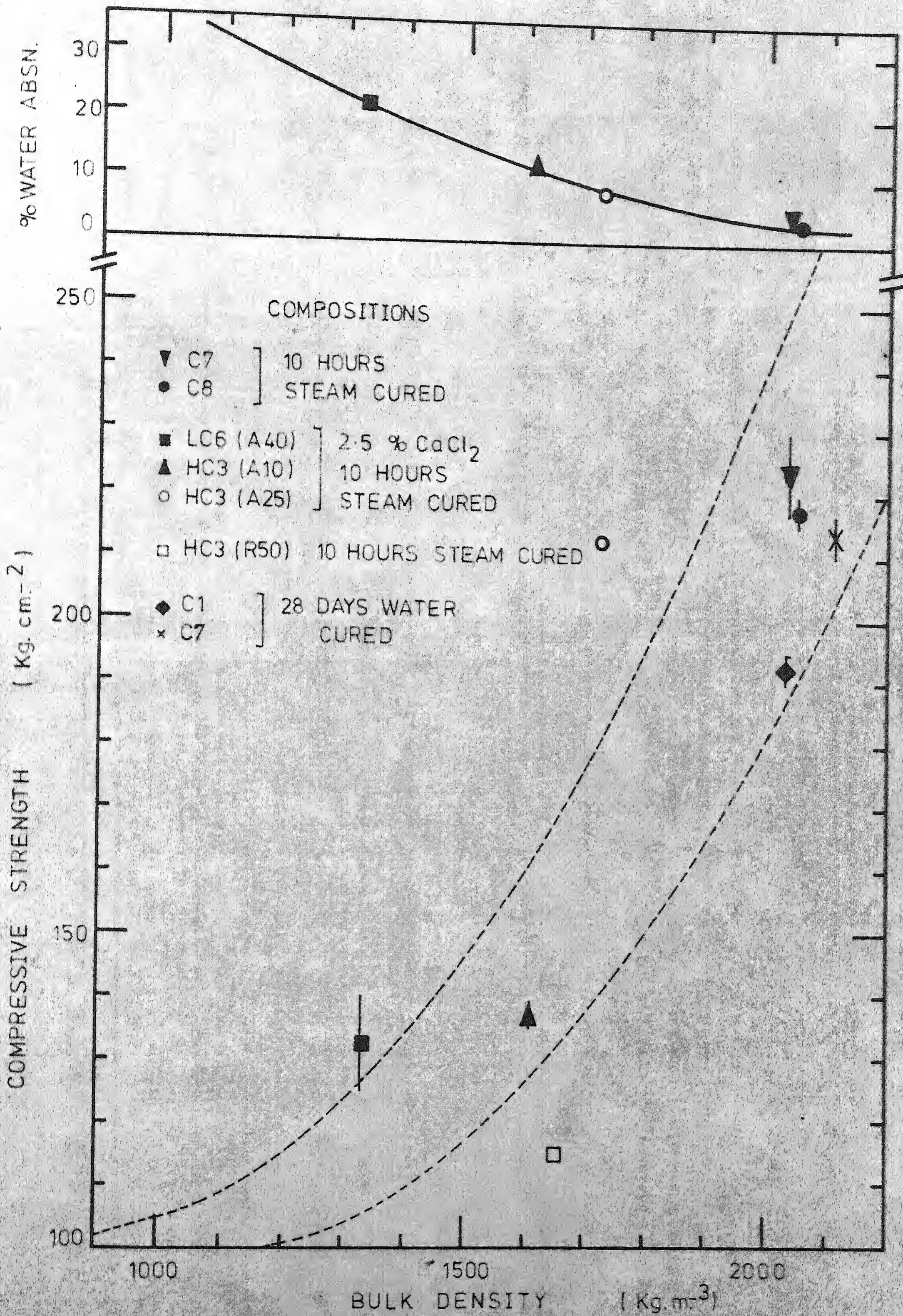


Fig. 5·23 COMPRESSIVE STRENGTH, BULK DENSITY & WATER ABSORPTION OF STANDARD SAMPLES.

CHAPTER - 6

CONCLUSIONS

(1) Following are the final lightweight concrete compositions:

	C1	C2	C7	HC3 (R50)	HC3 (A10)	HC3 (A25)	LC6 (A40)	C8
Composition								
Ashmoh	30	30	25	15	30	30	30	22.2
Rice husk ash	-	10.5	-	21	21	21	63	-
Sand	70	59.5	75	49	49	49	7	77.8
Total	100	100	100	85	100	100	100	100
Portland cement	-	-	-	15	10	25	40	-
Water to cement ratio	0.45	0.76	0.47	0.911	0.719-0.767	0.553-0.591	0.946-1.000	0.49
Additive-by weight of total cement	-	-	-	-	2.5% $CaCl_2$	-	-	-
Curing procedure (28 days water curing or 10 hours steam-curing can be used alternatively)	28 days water curing	28 days water curing	10 hours steam-curing	10 hours steam curing	10 hours steam curing	10 hours steam curing	10 hours steam curing	10 hours steam curing

	C1	C2	C7	HC3 (R50)	HC3 (A10)	HC3 (A25)	LC6 (A40)	C8
<u>Properties</u>								
Bulk density (kg/m^3)	2037	1697-1725	2037	1655	1745-1759	1723	1328	2051
Compressive strength (kg/cm^2)	190-195	86-88	217-230	115	210-211	211-214	125-140	215-220
<u>Compressive strength</u>								
Bulk density (10 m)	94.53	50.85	106.113	69.5	119.121	122-124	94-106	105-108
Water absorption (%)	-	-	3.78	-	12.25	8.04	21.89	3.44
Shrinkage (%)	-	-	0.043-0.060	-	0.0175	0.009-0.0175	0.0345-0.043	0.026
Thermal conductivity (kcal/m.hr.°C)	0.298-0.496	0.211-0.372	0.298-0.496	0.211-0.372	0.211-0.372	0.211-0.372	0.211-0.298	0.298-0.496

(2) Thermal conductivity: Apparatus for thermal conductivity was not available. The values are expected close to those of lightweight aggregate concretes. Hence the values in the table above are that of lightweight aggregate concretes (Ref. p. 490 (29)).

(3) Additive: Only on one composition (HC3 (A10)) 2.5% $CaCl_2$ has been tried. Seeing its effect on the composition we can expect 2.5% $CaCl_2$ to have similar effect on C2, HC3 (R50), HC3 (A25) and LC6 (A40) compositions and hence it is recommended for these compositions.

We conclude that it is possible to manufacture lightweight concrete in the range of bulk densities that have acceptable properties.

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APPENDIX - 1

CHARACTERIZATION OF ASHMOH, SAND AND RICE HUSK ASH

A.1.1 Bulk Density (Tapped Density):

(a) Ashmoh: Mass 500 g

Tapped Volume 525 cc

Bulk Density $= \frac{500\ g}{525\ cc} = 952\ kg/m^3$

(b) Sand: Mass 100 g

Tapped Volume 61.5 cc

Bulk Density $= \frac{100\ g}{61.5\ cc} = 1626\ kg/m^3$

(c) Rice Husk Ash: Mass 100 g

Tapped Volume 305 cc

Bulk Density $= \frac{100\ g}{305\ cc} = 328\ kg/m^3$

A.1.2 True Density (Specific Gravity):

(a) Ashmoh: Acetone density = 0.791 g/cc

	Set 1	Set 2
Mass of Bottle	24.0971 g	24.1103 g
Mass of (Bottle+Ashmoh)	36.9511 g	40.7271 g
Mass of (Bottle+ Ashmoh+Acetone)	71.3024 g	73.9560 g
Mass of (Bottle+ 50 cc Acetone)	63.327 g	63.6603 g
Mass of Ashmoh	(36.9511-24.0971)g = 12.8540 g	(40.7271-24.1103)g = 16.6168 g
Mass of acetone equivalent to volume of Ashmoh	((63.3270-24.0971)-(71.3024-36.9511))g = (39.2299-34.3513)g = 4.8786 g	((63.6603-24.1103)-(73.9560-40.7271))g = (39.5500-33.2289)g = 6.3211 g

Volume of Ashmoh	(4.8786/0.791) cc	(6.3211/0.791) cc
True density of Ashmoh	$(\frac{12.8540}{4.8786}\times 0.791)$g/cc	$(\frac{16.6168}{6.3211}\times 0.791)$g/cc
	= 2.086 g/cc	= 2.079 g/cc

Average true density of Ashmoh = 2082.5 kg/m^3

(b) Sand: Mass of sand sample 100 gm

Volume of sand + 40 cc water = 79.5 cc

True volume of sand = (79.5-40.0) = 39.5 cc

True density of sand = $\frac{100 \text{ g}}{39.5 \text{ cc}}$ = 2532 kg/m^3

A.1.3 Particle Size Distribution:

In terms of cumulative mass per cent passing through a sieve.

Mesh No.	Mesh size (10^{-6} m)	Unsieved RHA		Sieved RHA		Sand	
		a	b	a	b	a	b
>10	>2000	1000.0	100.0				
10	2000	968.5	96.85				
12	1680	944.4	94.44				
16	1190	897.2	89.72			500.00	100.00
18	1000	858.4	85.84			485.6903	97.138
20	840	806.9	80.69	806.9	100.0	-	-
35	500	670.4	67.04	670.4	83.083	203.7973	40.760
40	420	595.9	59.59	595.9	73.851	122.7887	24.558
45	350	532.9	53.29	532.9	66.043	66.9087	13.382
50	297	471.9	47.19	471.9	58.483	37.3231	7.465
70	210	312.4	31.24	312.4	38.716	14.5207	2.904
100	149	-	-	-	-	10.934	2.187
120	125	198.9	19.89	198.9	24.65	9.898	1.980
140	105	-	-	-	-	8.8364	1.767
170	88	156.9	15.69	156.9	19.445	-	-
200	74	127.0	12.70	127.0	15.739	6.6817	1.336
270	53	22.0	2.2	22.0	2.726		
325	44	20.0	2.0	20.0	2.0		

a-stands for - Mass passing through the sieve (g)
b-stands for - Per cent by wt. passing through the sieve.

A.1.4 Fineness of Ashmoh Cement (Blaine Specific Surface Area):

Room Temperature 24.5°C

(a) Calibration: Bulk volume of the packed bed

Mass of sample = 2.8 g

	Set - 1	Set - 2
Mass of mercury+beaker (no sample in the cell)	133.5727 g	133.910 g
Mass of mercury+beaker (sample in the cell)	109.6820 g	109.600 g
Mass of mercury equivalent to bulk volume of the packed bed	(133.5727-109.6820)g = 23.8907 g	(133.910-109.600)g = 24.310 g
Bulk volume of the packed bed	$\frac{23.8907 \text{ g}}{13.5380 \text{ g/cc}}$ = 1.7647 cc	$\frac{24.310 \text{ g}}{13.538 \text{ g/cc}}$ = 1.7957 cc

Error in the bulk volume calibration = 1.73%

Mass of portland cement (standard sample) required for the packed bed of 0.5 porosity

$= \rho V(1 - e)$

$= (3.15 \text{ g/cc}).(1.7647 \text{ cc}).(0.5)$

$= 2.7794 \text{ g}$

Mass of Ashmoh cement required for the packed bed of 0.5 porosity

$= \rho V(1 - e)$

$= (2.0825 \text{ g/cc}).(1.7647 \text{ cc}).(0.5)$

$= 1.8406 \text{ g}$

(b) Portland Cement Sample: Specific surface area = 2250 cm^2/g

	Time taken for a fixed volume of air to pass through the portland cement bed (seconds)
Sample No. 1	165.3
	167.0
	165.0
Sample No. 2	158.0
	157.8
	157.6
	157.5
	157.5
Sample No. 3	160.0
	159.8
	159.0
	158.6
Steady state average	158.31

(c) Ashmoh Cement Sample:

	Time taken for a fixed volume of air to pass through the Ashmoh cement bed (seconds)
Sample No. 1	203.40
	201.23
	200.67
	199.65
Sample No. 2	206.52
	204.28
	200.80
	201.68
Sample No. 3	205.44
	202.21
	201.71
Steady state average	202.51

(d) Specific Surface Area of Ashmoh Cement:

$$S = S_s \cdot \frac{\rho_s}{\rho} \cdot \sqrt{\frac{T}{T_s}}$$

$$= (2250\ cm^2/g)\left(\frac{3.15\ g/cc}{2.0825\ g/cc}\right) \cdot \sqrt{\frac{202.51}{158.31}}$$

$$= 3850\ cm^2/g.$$

APPENDIX - 2

EXPERIMENTAL MEASUREMENTS OF TENSILE STRENGTH TESTS

Abbreviations used	Abbreviation
Water to cement ratio by weight	W/C
Mass in grams (10^{-3} kg)	M
Height in cm (10^{-2} m)	H
Diameter in cm (10^{-2} m)	D
Bulk density in g/cm^3 ($\frac{10^3 kg}{m^3}$)	B.D.
Volume in cm^3 (10^{-6} m^3)	V
Breaking load in (kg)	B.L.
Tensile strength in (kg/cm^2)	T.S.
Tensile strength/Bulk density in $\frac{kg/cm^2}{g/cm^3}$ ($\frac{10^{-3}\ kg/cm^2}{kg/m^3}$)	$\frac{T.S.}{B.D.}$
Rice Husk Ash	RHA
Readings not considered	*
Average	Av.

Machine - 'INSTRON'

Strain rate 10 mm per min

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.

A.2.1 Binary Mixtures:

Ashmoh:RHA = 1:1

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
1.1	111	3.53	6.87	130.85	0.8463	48.0*	1.26	-
	107	3.50	6.87	129.74	0.8247	65.0	1.721	2.087
	107	3.52	6.87	130.48	0.8200	85.5	2.251	2.745
	106	3.50	6.87	129.74	0.8170	65.0	1.721	2.106
	118	3.52	6.90	131.62	0.8965	93.5	2.451	2.734
	107	3.52	6.88	130.86	0.8177	65.0	1.709	2.090
				Av.	0.8255	74.8	1.9706	2.3524
1.13	120	3.52	6.88	130.86	0.9170	81.5	2.1424	2.3360
	122	3.50	6.88	130.12	0.9338	95.0	2.5120	2.6900
	114	3.52	6.87	130.48	0.8737	75.0	1.9740	2.2590
	117	3.56	6.89	132.73	0.8815	81.5	2.1153	2.4000
	110	3.50	6.87	129.74	0.8479	44.5*	1.1782	-
	114	3.44	6.87	127.52	0.8940	99.5	2.6800	2.9980
				Av.	0.8913	86.5	2.2847	2.537
1.27	120	3.56	6.88	132.35	0.9067	54.0*	1.4036	-
	118	3.53	6.89	131.61	0.8966	96.0	2.5130	2.8030
	115	3.52	6.87	130.48	0.8814	91.0	2.3960	2.7180
	114	3.52	6.88	130.86	0.8712	97.5	2.5630	2.9420
	115	3.48	6.88	129.37	0.8889	86.0	2.2870	2.5730
	117	3.53	6.89	131.61	0.8890	109.0	2.8530	3.2090
				Av.	0.8890	95.9	2.5224	2.8490
1.2	95	3.50	6.84	128.61	0.7387	-	1.5960	2.162
	95	3.51	6.85	129.35	0.7344	60.0	1.5890	2.164
	90	3.43	6.86	126.77	0.7099	-	-	-
	97	3.53	6.86	130.47	0.7435	56.0	1.472	1.980
	94	3.50	6.86	129.36	0.7266	40.0*	-	-
	97	3.52	6.86	130.10	0.7456	55.0	1.450	1.945
				Av.	0.7315	57.0	1.527	2.063
1.23	106	3.53	6.89	131.61	0.8054	50.0*	1.309	-
	110	3.50	6.88	130.12	0.8454	76.5	2.022	2.392
	104	3.48	6.88	129.37	0.8039	82.5	2.194	2.729
	107	3.51	6.87	130.11	0.8224	156.5*	-	-
	111	3.53	6.88	131.23	0.8423	70.0	1.835	2.179
	118	3.51	6.88	130.49	0.7997	90.0	2.373	2.967
				Av.	0.8199	79.8	2.106	2.569

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
1.27	102	3.54	6.87	131.22	0.7773	58.0	1.518	1.953
	103	3.54	6.87	131.22	0.7849	71.0	1.859	2.368
	105	3.50	6.87	129.74	0.8093	84.0	2.224	2.748
	103	3.54	6.86	130.84	0.7872	65.0	1.704	2.165
	103	3.54	6.87	131.22	0.7849	58.5	1.531	1.951
	83	3.26	6.86	120.49	0.6889	30.0*	-	-
				Av.	0.7721	67.3	1.767	2.289

<u>Ashmoh:RHA = 1:2</u>

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
1.9	80	3.52	6.83	128.97	0.6203	20.0	0.530	0.854
	79	3.55	6.86	131.21	0.6021	20.0	0.523	0.869
	80	3.53	6.83	129.33	0.6186	18.0	0.475	0.768
	81	3.56	6.86	131.58	0.6156	18.0	0.469	0.762
	80	3.57	6.85	131.56	0.6081	19.0	0.495	0.814
	78	3.54	6.86	130.84	0.5961	16.0	0.419	0.703
				Av.	0.6101	18.5	0.485	0.795
2.0	79	3.55	6.87	131.59	0.6003	12.5	0.326	0.543
	80	3.55	6.86	130.21	0.6097	18.0	0.471	0.773
	80	3.55	6.85	130.83	0.6115	17.5	0.458	0.749
	85	3.55	6.88	131.98	0.6441	21.5	0.560	0.869
	76	3.55	6.88	131.98	0.5758	14.0	0.365	0.634
	82	3.50	6.87	129.74	0.6320	20.0	0.530	0.839
				Av.	0.6122	17.3	0.452	0.735
2.2	91	3.55	6.87	131.59	0.6915	25.0	0.653	0.944
	92	3.55	6.90	132.74	0.6930	26.5	0.689	0.994
	85	3.55	6.84	130.45	0.6516	21.0	0.551	0.846
	89	3.54	6.87	131.22	0.6782	18.5	0.484	0.714
	90	3.54	6.86	131.95	0.6821	20.0	0.524	0.768
	94	3.57	6.88	132.72	0.7083	24.3	0.630	0.889
				Av.	0.6841	22.6	0.589	0.861
2.4	95	3.56	6.84	130.81	0.7262	21.5	0.562	0.774
	95	3.55	6.84	130.45	0.7283	22.0	0.577	0.792
	94	3.56	6.84	130.81	0.7186	28.5	0.739	1.028
	96	3.56	6.87	131.96	0.7275	21.0	0.547	0.752
	97	3.57	6.87	132.33	0.7330	24.0	0.623	0.850
	96	3.52	6.86	130.10	0.7379	23.0	0.606	0.821
				Av.	0.7286	23.3	0.609	0.836

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
Ashmoh:RHA = 1:3								
3.33	90	3.55	6.87	131.59	0.6839	15.0	0.392	0.573
	86	3.49	6.85	128.62	0.6687	12.5	0.333	0.498
	90	3.56	6.86	131.58	0.6840	15.0	0.391	0.572
	86	3.53	6.85	130.09	0.6611	12.0	0.316	0.478
	86	3.53	6.85	130.09	0.6611	12.0	0.316	0.478
	85	3.52	6.85	129.72	0.6552	12.8	0.338	0.516
				Av.	0.6690	13.22	0.348	0.520
3.5	90	3.56	6.89	132.73	0.6781	14.5	0.376	0.555
	90	3.57	6.84	131.18	0.6861	17.0	0.443	0.646
	90	3.56	6.86	131.58	0.6840	14.5	0.378	0.553
	91	3.56	6.84	130.81	0.6956	15.5	0.405	0.582
	91	3.61	6.86	133.43	0.6820	14.5	0.373	0.547
	88	3.56	6.84	130.81	0.6727	16.0	0.418	0.621
				Av.	0.6831	15.3	0.399	0.584
3.67	88	3.58	6.82	130.78	0.6729	9.0	0.235	0.349
	88	3.56	6.85	131.20	0.6708	11.0	0.287	0.428
	88	3.61	6.87	133.82	0.6576	12.0	0.308	0.468
	87	3.54	6.85	130.46	0.6669	10.0	0.263	0.394
	89	3.62	6.83	132.63	0.6710	12.2	0.314	0.468
	89	3.57	6.86	131.95	0.6745	13.4	0.348	0.516
				Av.	0.6690	11.3	0.293	0.438
3.83	87	3.60	6.84	132.28	0.6577	8.5	0.220	0.335
	86	3.60	6.86	133.06	0.6463	–	–	–
	86	3.64	6.85	134.83	0.6601	8.0	0.204	0.309
	89	3.61	6.86	133.43	0.6670	8.5	0.216	0.324
	88	3.59	6.87	133.08	0.6613	10.0	0.258	0.390
	89	3.67	6.86	135.65	0.6561	7.5	0.190	0.290
				Av.	0.6581	8.5	0.218	0.331
Ashmoh:Sand = 1:3								
0.533	277	3.74	6.85	–	2.0097	833	20.7	10.3
	275	3.75	6.86	–	1.9841	756	18.710	9.43
	277	3.77	6.84	–	2.0113	698	17.232	8.568
	277	3.78	6.84	–	1.9943	672	16.546	8.297
	279	3.81	6.86	–	1.9813	–	–	–
				Av.	1.9961	739.8	18.297	9.17

W/C	M	H	D	V	B.D.	B.L.	T.S.	$\frac{T.S.}{B.D.}$
0.47	279	3.76	6.85	-	2.0135	993	24.544	12.19
	283	3.77	6.87	-	2.0251	924	22.712	11.215
	285	3.84	6.86	-	2.0258	1040	25.134	12.407
	285	3.81	6.84	-	2.0357	1070	26.139	12.84
	290	3.88	6.86	-	2.0222	-	-	-
	282	3.78	6.82	-	2.0422	-	-	-
				Av.	2.0274	1006.8	24.632	12.15
0.412	272	3.66	6.88	-	1.9990	837	21.161	10.586
	271	3.66	6.87	-	1.9975	873	22.103	11.065
	275	3.70	6.86	-	2.0109	930	23.326	11.60
	267	3.64	6.87	-	1.9788	800	20.366	10.292
	278	3.71	6.87	-	2.0215	-	-	-
	269	3.61	6.87	-	2.0102	-	-	-
				Av.	2.0030	860	21.739	10.85

<u>Ashmoh:Sand = 1:4</u>

0.5	269	3.71	6.87	-	1.9560	604	15.086	7.713
	266	3.63	6.88	-	1.9711	487	12.414	6.298
	272	3.67	6.88	-	1.9936	532	13.413	6.728
	267	3.64	6.87	-	1.9788	518	13.187	6.664
	272	3.65	6.89	-	1.9987	-	-	-
	263	3.61	6.88	-	1.9597	-	-	-
				Av.	1.9763	535.3	13.525	6.844
0.57	277	3.81	6.86	-	1.9671	528	12.861	6.538
	275	3.77	6.87	-	1.9678	569	14.251	7.242
	269	3.62	6.85	-	2.0164	470	12.066	5.984
	270	3.70	6.88	-	1.9629	-	-	-
	269	3.61	6.87	-	2.0102	482	12.373	6.155
	269	3.71	6.87	-	1.9560	-	-	-
				Av.	1.9801	512.3	12.888	6.509
0.444	268	3.65	6.87	-	1.9808	380	9.647	4.870
	269	3.57	6.89	-	2.0209	515	13.329	6.596
	253	3.63	6.87	-	1.8802	-	-	-
	252	3.61	6.85	-	1.8942	360	9.268	4.893
	261	3.60	6.90	-	1.9362	-	-	-
	259	3.61	6.88	-	1.9299	-	-	-
				Av.	1.9404	418.3	10.748	5.54

W/C	M	H	D	V	B.D.	B.L.	T.S.	$\frac{T.S.}{B.D.}$
Ashmoh:Sand = 1:5								
0.533	267	3.79	6.89	-	1.8895	-	-	-
	256	3.69	6.89	-	1.8607	237	5.934	3.189
	255	3.72	6.89	-	1.8385	245	6.085	3.310
	256	3.72	6.86	-	1.8619	295	7.359	3.952
	257	3.72	6.88	-	1.8583	288	7.164	3.855
	253	3.70	6.88	-	1.8393	-	-	-
				Av.	1.8580	266.3	6.636	3.572
0.617	274	3.86	6.88	-	1.9094	370	8.870	4.645
	265	3.75	6.89	-	1.8953	308.5	7.601	4.01
	260	3.70	6.88	-	1.8902	296	7.403	3.917
	267	3.77	6.87	-	1.9106	370	9.095	4.76
	269	3.75	6.87	-	1.9352	-	-	-
	258	3.66	6.87	-	1.9017	-	-	-
				Av.	1.9071	336.1	8.242	4.322
0.467	258	3.74	6.89	-	1.8502	275	6.794	3.672
	253	3.77	6.87	-	1.8104	297	7.300	4.032
	252	3.74	6.86	-	1.8230	258.5	6.414	3.518
	255	3.72	6.88	-	1.8439	298.5	7.425	4.027
	245	3.65	6.89	-	1.8003	-	-	-
	247	3.60	6.87	-	1.8509	-	-	-
				Av.	1.8298	282.3	6.983	3.820
Ashmoh:Sand = 1:6								
0.588	255	3.76	6.88	-	1.8243	237	5.832	3.197
	258	3.81	6.90	-	1.8109	257.5	6.236	3.444
	253	3.81	6.90	-	1.7759	213	5.158	2.904
	251	3.77	6.90	-	1.7805	227.5	5.568	3.127
	253	3.77	6.88	-	1.8051	-	-	-
	252	3.77	6.90	-	1.7876	-	-	-
				Av.	1.7974	233.8	5.569	3.098
0.667	260	3.80	6.88	-	1.8404	207	5.041	2.739
	256	3.74	6.87	-	1.8466	218	5.401	2.925
	262	3.83	6.88	-	1.8401	212.5	5.134	2.79
	262	3.81	6.89	-	1.8444	235	5.699	3.09
	256	3.73	6.87	-	1.8515	-	-	-
				Av.	1.8446	218.1	5.319	2.884

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
0.51	249	3.80	6.88	-	1.7626	180	4.383	2.487
	249	3.77	6.87	-	1.7818	200	4.916	2.759
	248	3.70	6.88	-	1.8029	172	4.301	2.386
	246	3.69	6.90	-	1.7829	-	-	-
	248	3.79	6.86	-	1.7704	167	4.089	2.310
	245	3.70	6.90	-	1.7708	-	-	-
				Av.	1.7786	179.8	4.422	2.486

A.2.2 <u>Ternary Mixtures:</u>

<u>Ashmoh:RHA:Sand = 1:1:0.5</u>

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
0.925	119	3.58	6.86	132.32	0.8993	62.5	1.620	1.801
	126	3.56	6.89	-	0.9493	72.3	1.876	1.976
	120	3.56	6.86	-	0.9120	86.8	2.263	2.482
	124	3.60	6.87	-	0.9292	74.5	1.918	2.064
	123	3.58	6.87	-	0.9269	-	-	-
	123	3.61	6.86	-	0.9218	-	-	-
				Av.	0.9231	74.0	1.919	2.079
1.03	126	3.55	6.87	-	0.9575	70.0	1.827	1.908
	130	3.55	6.85	-	0.9937	94.0	2.461	2.477
	130	3.49	6.87	-	1.0049	90.0	2.390	2.378
	133	3.61	6.87	-	0.9939	89.0	2.285	2.299
	125	3.55	6.90	-	0.9417	-	-	-
	130	3.58	6.87	-	0.9796	-	-	-
				Av.	0.9786	85.8	2.241	2.29
1.187	144	3.69	6.86	-	1.0558	110	1.766	2.620
	138	3.63	6.87	-	1.0256	110	2.808	2.738
	136	3.57	6.87	-	1.0277	100	2.596	2.525
	142	3.69	6.87	-	1.0381	102	2.562	2.468
	131	3.57	6.86	-	0.9928	-	-	-
	125	3.50	6.87	-	0.9635	-	-	-
				Av.	1.0173	105.5	2.683	2.637
1.28	136	3.70	6.86	-	1.0033	65	1.630	1.625
	138	3.74	6.86	-	0.9983	75	1.861	1.864
	136	3.68	6.86	-	0.9990	57	1.437	1.438
	136	3.72	6.84	-	0.9949	74	1.851	1.861
	139	3.76	6.89	-	0.9915	-	-	-
	128	3.52	6.87	-	0.9810	-	-	-
				Av.	0.9947	67.8	1.695	1.704

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
Ashmoh:RHA:Sand = 1:1:1.07								
1.077	140	3.57	6.87	132.33	1.0579	107.5	2.790	2.637
	141	3.57	6.88	132.72	1.0624	92.0	2.385	2.245
	140	3.54	6.86	130.84	1.0700	105.0	2.753	2.573
	136	3.54	6.88	131.60	1.0334	60.0*	1.568	-
	144	3.58	6.87	132.70	1.0851	-	-	-
	141	3.51	6.88	130.49	1.0806	-	-	-
				Av.	1.0649	101.5	2.643	2.485
1.2	147	3.59	6.86	132.69	1.1079	98.0*	2.533	-
	140	3.61	6.90	134.99	1.0371	66.0	1.687	1.627
	147	3.61	6.87	133.82	1.0985	73.0	1.874	1.706
	145	3.57	6.88	132.72	1.0925	67.0	1.737	1.590
	145	3.58	6.87	132.70	1.0927	-	-	-
	145	3.56	6.86	131.58	1.1020	-	-	-
				Av.	1.0885	68.7	1.766	1.641
1.323	150	3.68	6.87	136.41	1.0996	73.0	1.838	1.672
	147	3.54	6.86	130.84	1.1235	74.0	1.940	1.727
	150	3.66	6.86	135.28	1.1088	69.0	1.750	1.578
	149	3.70	6.86	136.75	1.0895	68.0	1.706	1.566
	149	3.68	6.86	136.01	1.0955	-	-	-
	149	3.67	6.88	136.44	1.0921	-	-	-
				Av.	1.1015	71.0	1.809	1.642
1.446	145	3.71	6.85	136.72	1.0605	46	1.152	1.086
	145	3.67	6.86	135.65	1.0690	50	1.264	1.182
	146	3.69	6.88	137.18	1.0643	36*	0.903	-
	145	3.77	6.87	139.75	1.0376	47	1.155	1.113
	146	3.70	6.88	137.55	1.0614	-	-	-
	145	3.70	6.86	136.75	1.0603	-	-	-
				Av.	1.0589	47.7	1.190	1.124
Ashmoh:RHA:Sand = 1:1:2								
1.33	159	3.53	6.85	130.09	1.2222	69	1.817	1.487
	158	3.51	6.87	130.11	1.2144	73	1.927	1.587
	156	3.54	6.88	131.60	1.1854	58	1.516	1.279
	154	3.53	6.87	130.85	1.1769	50	1.313	1.116
	156	3.51	6.88	130.49	1.1955	64	1.687	1.411
	159	3.52	6.87	130.48	1.2186	60.5	1.593	1.307
	161	3.55	6.85	130.83	1.2306	60	1.571	1.277
				Av.	1.2205	62.1	1.632	1.352

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
1.6	160	3.71	6.88	137.92	1.1601	52.0	1.297	1.118
	157	3.56	6.86	131.58	1.1932	42.0	1.095	0.918
	157	3.66	6.85	134.88	1.1640	74.0*	1.879	-
	156	3.63	6.86	134.17	1.1627	47.0	1.202	1.034
	155	3.67	6.85	135.14	1.1470	47.5	1.203	1.049
	157	3.68	6.85	135.62	1.1577	52.0	1.313	1.134
				Av.	1.1641	48.1	1.222	1.0506
1.44	166	3.72	6.86	137.49	1.2073	78.5	1.958	1.622
	162	3.66	6.85	134.88	1.2011	60.0	1.524	1.269
	165	3.66	6.87	135.67	1.2162	62.5	1.582	1.301
	166	3.73	6.88	138.67	1.1935	56.0	1.389	1.164
	164	3.68	6.86	136.01	1.2058	58.0	1.463	1.213
	165	3.67	6.86	135.65	1.2164	57.5	1.454	1.195
				Av.	1.2067	62.1	1.562	1.294
1.52	163	3.68	6.84	135.22	1.2054	65.0	1.644	1.364
	162	3.67	6.85	135.25	1.1978	71.5	1.811	1.512
	162	3.68	6.87	136.41	1.1876	59.0	1.486	1.251
	162	3.73	6.87	138.26	1.1717	62.5	1.553	1.325
	162	3.65	6.86	135.02	1.1998	62.0	1.576	1.314
	160	3.72	6.86	137.49	1.1637	53.0*	1.322	-
				Av.	1.1877	64.0	1.614	1.359

Ashmoh:RHA:Sand = 1:2:0.75

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
1.784	114	3.49	6.88	-	0.8786	40*	1.061	-
	113	3.57	6.88	-	0.8514	25	0.648	0.761
	124	3.52	6.87	-	0.9503	-	-	-
	112	3.52	6.88	-	0.8559	25.5	0.670	0.783
	116	3.56	6.85	-	0.8842	29.5	0.770	0.871
	121	3.56	6.86	-	0.9196	-	-	-
				Av.	0.8900	26.7	0.696	0.782
2.019	120	3.50	6.89	-	0.9196	29.0	0.766	0.834
	120	3.53	6.88	-	0.9144	44.8	1.174	1.284
	118	3.53	6.86	-	0.9044	28.8	0.757	0.837
	119	3.55	6.88	-	0.9017	37.0	0.964	1.069
	115	3.63	6.89	-	0.8497	-	-	-
	120	3.60	6.88	-	0.8966	-	-	-
				Av.	0.8977	34.9	0.915	1.019

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
2.253	125	3.72	6.85	-	0.9118	28.6	0.715	0.784
	124	3.72	6.87	-	0.8992	26.5	0.660	0.734
	125	3.73	6.87	-	0.9041	24.4	0.606	0.670
	124	3.73	6.86	-	0.8994	26.8	0.667	0.742
	123	3.76	6.84	-	0.8903	-	-	-
	120	3.67	6.88	-	0.8795	-	-	-
				Av.	0.8974	26.6	0.662	0.738
2.488	119	3.73	6.86	-	0.8632	18.0	0.448	0.519
	120	3.78	6.87	-	0.8564	17.0	0.417	0.487
	119	3.78	6.85	-	0.8542	18.0	0.443	0.519
	118	3.77	6.85	-	0.8493	15.2	0.375	0.442
	120	3.74	6.88	-	0.8631	-	-	-
	122	3.80	6.88	-	0.8636	-	-	-
				Av.	0.8583	17.1	0.421	0.491

Ashmoh:RHA:Sand = 1:2:1.3

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
2.38	133	3.72	6.86	-	0.9673	26.3	0.656	0.678
	137	3.77	6.87	-	0.9803	24.0	0.590	0.602
	133	3.72	6.84	-	0.9730	22.3	0.558	0.574
	129	3.61	6.87	-	0.9640	22.0	0.565	0.586
	127	3.59	6.86	-	0.9571	-	-	-
	128	3.62	6.86	-	0.9567	-	-	-
				Av.	0.9664	23.7	0.592	0.613
2.189	133	3.60	6.86	-	0.9996	35.0	0.902	0.902
	131	3.57	6.86	-	0.9928	39.8	1.035	1.043
	130	3.55	6.85	-	0.9937	26.5	0.694	0.698
	132	3.76	6.88	-	0.9443	30.0	0.738	0.782
	137	3.67	6.87	-	1.0070	-	-	-
	133	3.66	6.87	-	0.9803	-	-	-
				Av.	0.9863	32.8	0.842	0.854
1.973	139	3.66	6.86	-	1.0275	54.0*	1.369	-
	123	3.50	6.88	-	0.9453	-	-	-
	133	3.69	6.87	-	0.9723	32.8	0.824	0.848
	133	3.65	6.88	-	0.9801	35.5	0.900	0.918
	130	3.52	6.88	-	0.9934	37.5	0.986	0.993
	135	3.70	6.84	-	0.9930	-	-	-
				Av.	0.9853	35.3	0.903	0.917

/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
2.62	128	3.70	6.86	-	0.9360	14.5	0.364	0.389
	128	3.77	6.86	-	0.9186	17.2	0.423	0.461
	128	3.74	6.87	-	0.9233	24.5*	0.607	-
	127	3.68	6.37	-	0.9310	14.0	0.353	0.379
	127	3.80	6.86	-	0.9042	-	-	-
	132	3.76	6.87	-	0.9471	-	-	-
				Av.	0.9267	15.2	0.380	0.410

Ashmoh:RHA:Sand = 1:2:2

/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
3.0	132	3.76	6.85	-	0.9526	11.5	0.284	0.298
	132	3.82	6.85	-	0.9376	11.6	0.282	0.301
	128	3.71	6.85	-	0.9362	10.6	0.266	0.284
	129	3.78	6.85	-	0.9260	10.5	0.258	0.279
	135	3.83	6.86	-	0.9537	-	-	-
	132	3.74	6.87	-	0.9521	-	-	-
	128	3.78	6.85	-	0.9189	-	-	-
				Av.	0.9396	11.1	0.273	0.291
2.75	132	3.64	6.84	-	0.9869	13.2	0.338	0.343
	139	3.82	6.86	-	1.0105	16.0	0.389	0.385
	131	3.70	6.88	-	0.9524	-	-	-
	137	3.81	6.86	-	0.9729	16.7	0.407	0.418
	135	3.82	6.84	-	0.9618	13.0	0.317	0.330
	132	3.70	6.88	-	0.9596	-	-	-
				Av.	0.9740	14.7	0.363	0.373
2.5	140	3.71	6.86	-	1.0210	21.5	0.538	0.527
	142	3.80	6.85	-	1.0140	22.8	0.558	0.550
	140	3.78	6.84	-	1.0079	16.6	0.409	0.406
	143	3.83	6.88	-	1.0043	20.6	0.498	0.496
	144	3.82	6.86	-	1.0199	-	-	-
	139	3.75	6.84	-	1.0087	-	-	-
				Av.	1.0126	20.4	0.501	0.495
2.11	149	3.71	6.86	-	1.0866	35.5	0.888	0.817
	137	3.52	6.88	-	1.0469	32.0	0.841	0.803
	139	3.52	6.87	-	1.0653	26.0	0.684	0.642
	141	3.58	6.87	-	1.0625	28.0	0.725	0.683
	141	3.55	6.86	-	1.0746	-	-	-
	140	3.57	6.85	-	1.0641	-	-	-
				Av.	1.0667	30.4	0.784	0.735

W/C	M	H	D	V	B.D.	B.L.	T.S.	T.S./B.D.
Ashmoh:RHA:Sand = 1:3:1								
3.929	105	3.82	6.81	-	0.7480	4.6	0.112	0.150
	106	3.72	6.86	-	0.7709	6.5	0.162	0.210
	104	3.86	6.83	-	0.7354	5.7	0.138	0.188
				Av.	0.7514	5.6	0.137	0.182
3.571	112	3.78	6.86	-	0.8017	8.0	0.196	0.245
	110	3.70	6.89	-	0.7974	6.8	0.170	0.213
	112	3.75	6.87	-	0.8057	7.1	0.175	0.217
	112	3.75	6.87	-	0.8057	8.3	0.205	0.254
	113	3.80	6.87	-	0.8022	-	-	-
	107	3.74	6.88	-	0.7696	-	-	-
				Av.	0.7971	7.6	0.187	0.235
3.214	108	3.62	6.85	-	0.8087	10.5	0.269	0.333
	113	3.71	6.86	-	0.8241	9.0	0.225	0.273
	108	3.60	6.86	-	0.8117	10.3	0.266	0.328
	108	3.61	6.85	-	0.8118	8.9	0.229	0.282
				Av.	0.8141	9.7	0.247	0.3034
Ashmoh:RHA:Sand = 1:3:2.67								
3.704	133	3.73	6.87	-	0.9619	7.4	0.184	0.191
	134	3.85	6.87	-	0.9389	6.8	0.164	0.175
	127	3.65	6.87	-	0.9387	7.8	0.198	0.211
	129	3.68	6.87	-	0.9457	7.0	0.176	0.186
	135	3.83	6.84	-	0.9593	-	-	-
	133	3.86	6.84	-	0.9377	-	-	-
				Av.	0.9470	7.3	0.181	0.191
3.33	135	3.73	6.86	-	0.9792	9.6	0.239	0.244
	131	3.70	6.85	-	0.9607	7.5	0.188	0.196
	134	3.76	6.85	-	0.9670	8.9	0.220	0.228
	137	3.81	6.87	-	0.9700	8.3	0.202	0.208
	137	3.84	6.84	-	0.9709	-	-	-
	132	3.76	6.86	-	0.9498	-	-	-
				Av.	0.9663	8.6	0.212	0.2194
4.074	124	3.75	6.80	-	0.8997	3.5	0.0874	0.097
	133	4.00	6.85	-	0.9022	3.6	0.0836	0.095
				Av.	0.9010	3.55	0.0855	0.096

APPENDIX - 3

EXPERIMENTAL MEASUREMENTS OF TENSILE STRENGTH AND COMPRESSIVE STRENGTH TESTS

Compositions:

C1	30 Ashmoh, 0 RHA, 70 Sand
C2	30 Ashmoh, 10.5 RHA, 59.5 Sand
C3	30 Ashmoh, 21 RHA, 49 Sand
C4	30 Ashmoh, 31.5 RHA, 38.5 Sand
C5	30 Ashmoh, 42 RHA, 28 Sand
C6	30 Ashmoh, 63 RHA, 7 Sand
C7	25 Ashmoh, 0 RHA, 75 Sand

A.3.1 Five hours steam-cured samples:

(a) Pellets

Composition	W/C	M	H	D	B.D.	B.L.	T.S.	$\frac{T.S.}{B.D.}$
C1	0.45	280	3.72	6.86	2.035	1306	34.53	16.97
		288	3.90	6.85	2.005	1133	29.95	14.94
		286	3.90	6.84	1.996	1166	30.83	15.45
	Av.	284.66	3.84	6.85	2.012	1202	31.78	15.80
C2	0.59*	205	3.58	6.87	1.545	432	11.42	7.39
		202	3.58	6.90	1.508	442	11.69	7.75
		215	3.58	6.88	1.618	442	11.69	7.23
	Av.	207.33	3.58	6.88	1.558	439	11.60	7.45
C3	0.76	237	3.72	6.87	1.717	478	12.64	7.36
		237	3.80	6.85	1.692	445	11.76	6.95
		242	3.77	6.86	1.737	354*	9.36	5.39
	Av.	238.7	3.76	6.86	1.717	462	11.84	6.90

Composition	W/C	M	H	D	B.D.	B.L.	T.S.	T.S./B.D.
C3	0.97	190	3.68	6.90	1.388	267	7.06	5.23
		180	3.62	6.90	1.330	213	5.62	4.23
		190	3.68	6.88	1.390	261	6.90	4.964
	Av.	186.7	3.66	6.89	1.368	247	6.53	4.774
C4	1.3	165	3.55	6.88	1.251	128	3.39	2.71
		169	3.62	6.85	1.267	122	3.23	2.55
		167	3.63	6.88	1.234	125	3.29	2.67
	Av.	167	3.60	6.87	1.251	125	3.30	2.64
C5	1.45	145	3.60	6.89	1.080	105	2.78	2.574
		140	3.60	6.87	1.048	104	2.75	2.624
		140	3.62	6.88	1.040	101	2.67	2.567
	Av.	141.7	3.61	6.88	1.053	103.3	2.73	2.593
C6	2.07	111	3.65	6.88	0.819	41.0	1.084	1.324
		115	3.49	6.87	0.887	45.0	1.190	1.342
		110	3.60	6.87	0.824	28.5*	0.75	0.910
	Av.	112	3.58	6.87	0.844	43.0	1.137	1.347
C7	0.47	292	3.85	6.85	2.058	910	24.06	11.69
		294	3.87	6.88	2.040	890	23.53	11.534
		285	3.73	6.87	2.059	860	22.74	11.045
	Av.	290.33	3.82	6.87	2.052	887	23.45	11.43

(b) Cubes: Cube Mass (M) in grams (10^{-3} kg)

Bulk Density (B.D.) = Cube Mass (M)/ Cube Volume (V) in (10^3 kg/m^3)

Compressive Strength (C.S.) in kg/cm^2

Cube face area = 50 cm^2 = 50(10^{-4} m^2)

C.S. = (B.L.)/Cube face area

Cube Volume (V) = 353.33 cm^3 = 353.33 (10^{-6} m^3)

Composition	W/C	M	B.D.	B.L.	C.S.	C.S./B.D.	C.S./T.S.	T.S./C.S. per cent
C1	0.45	715	2.022	8800	176	87.04	5.538	18.06
		725	2.051	8950	179	87.27	5.632	17.76
	Av.	720	2.0365	8875	177.5	87.15	5.5853*	17.91*
C2	0.70	600	1.698	3550	71	41.81	6.12	16.34
		610	1.726	3875	77.5	44.9	6.68	14.97
	Av.	605	1.711	371.5	74.25	43.40	6.27	15.93
C3	0.821*	440*	1.245	1650*	33*	26.51*	4.06	24.63
	0.97	512	1.448	2000	40	27.62	6.126	16.32
	Av.	512	1.448	2000	40	27.62	6.126	16.32
C4	1.3	415	1.174	1050	21	17.89	6.358*	15.71*
		435	1.230	1050	21	17.07	6.358*	15.71*
	Av.	425	1.202	1050	21	17.47	6.358*	15.71*
C5	1.45	377	1.066	650	13	12.20	4.76	21.01
		392	1.109	700	14	12.62	5.13	19.49
	Av.	384.5	1.0875	675	13.5	12.41	4.94	20.25
C6	2.07	312	0.883	400	8	9.06	7.04	14.20
		300	0.849	450	9	10.60	7.92	12.63
	Av.	306	0.8655	425	8.5	9.83	7.476*	13.38*
C7	0.47	760	2.150	7900	158	73.49	6.74	14.84
		735	2.082	7950	159	76.37	6.78	14.75
	Av.	747.5	2.114	7925	158.5	74.98	6.76	14.80

A.3.2 28 days water cured samples:

(a) Pellets:

Composition	W/C	M	H	D	B.D.	B.L.	T.S.	T.S./B.D.
C1	0.45	286	3.90	6.84	1.996	1000	24.88	12.47
		288	3.90	6.85	2.005	1205	28.72	14.32
		280	3.72	6.86	2.035	1350	32.22	15.83
	Av.	284.7	3.84	6.85	2.012	1185	28.68	14.25

Composition	W/C	M	H	D	B.D.	B.L.	T.S.	T.S./B.D.
C2	0.59*	202	3.58	6.90	1.508	393	10.17	6.74
		215	3.58	6.88	1.618	285*	7.35*	4.54
		205	3.58	6.87	1.545	426	11.01	7.13
	Av.	207.3	3.58	6.88	1.558	409.5	10.59	6.80
C2	0.76	237	3.80	6.85	1.692	510	12.70	7.51
		237	3.72	6.87	1.717	575	14.06	8.19
		242	3.77	6.86	1.737	510	12.55	7.23
	Av.	238.7	3.76	6.86	1.717	531.7	13.10	7.63
C3	0.97	190	3.68	6.88	1.390	275	6.89	4.96
		190	3.68	6.90	1.388	240	6.12	4.41
		180	3.62	6.90	1.330	315	7.92	5.96
	Av.	186.7	3.66	6.89	1.368	276.7	6.98	5.10
C4	1.3	165	3.55	6.88	1.251	178	4.64	3.71
		167	3.63	6.88	1.234	176	4.52	3.66
		169	3.62	6.85	1.267	198	5.05	3.99
	Av.	167	3.60	6.87	1.251	184	4.737	3.79
C5	1.45	145	3.60	6.89	1.080	126	3.23	2.99
		140	3.60	6.87	1.048	93	2.39	2.28
		140	3.62	6.88	1.040	117	2.99	2.88
	Av.	141.67	3.61	6.88	1.053	112	2.87	2.73
C6	2.07	115	3.49	6.87	0.887	47	1.19	1.34
		111	3.65	6.88	0.819	44.5	1.18	1.44
		110	3.60	6.87	0.824	33	0.85	1.03
	Av.	112	3.58	6.87	0.844	41.5	1.073	1.27
C7	0.47	292	3.85	6.85	2.058	1020	24.62	11.96
		285	3.73	6.87	2.059	980	23.43	11.38
		294	3.87	6.88	2.040	1205	29.94	14.68
	Av.	290.3	3.82	6.87	2.052	1068.3	25.997	12.67

(b) Cubes:

Composition	W/C	M	B.D.	B.L.	C.S.	C.S./B.D.	C.S./T.S.	T.S./C.S. per cent
C1	0.45	715	2.022	9750	195	96.44	6.80	14.71
		725	2.051	9500	190	92.64	6.63	15.08
	Av.	720	2.0365	9625	192.5	94.53	6.72	14.88
C2	0.70	600	1.698	4300	86	50.65	6.57	15.22
		610	1.726	4400	88	50.99	6.72	14.88
	Av.	605	1.711	4350	87	50.85	6.64	15.08
C3	0.821*	440*	1.245	1300*	26	20.88	3.72	26.88
	0.97	512	1.448	2550	51	35.22	7.307	13.69
	Av.	512	1.448	2550	51	35.22	7.307*	13.69*
C4	1.3	415	1.174	975	19.5	16.61	4.12	24.27
		435	1.230	1350	27	21.95	5.70	17.54
	Av.	425	1.202	1162.5	23.25	19.34	4.908	21.09
C5	1.45	377	1.066	900	18	16.89	6.27	15.95
		392	1.109	1075	21.5	19.39	7.49	13.35
	Av.	384.5	1.0875	987.5	19.75	18.16	6.881*	14.52*
C6	2.07	312	0.883	600	12	14.13	11.18	8.95
		300	0.849	600	12	14.13	11.18	8.95
	Av.	306	0.8655	600	12	13.87	11.18*	8.95*
C7	0.47	760	2.150	10850	217	100.93	8.38	11.93
		735	2.082	10500	210	100.87	8.08	12.38
	Av.	747.5	2.114	10675	213.5	100.90	8.215	12.18

APPENDIX - 4

EXPERIMENTAL MEASUREMENTS OF COMPRESSIVE STRENGTH TESTS

A.4.1 Upgrading of Compositions HC3 and LC6:

Composition codes: R .... 'Replacement'

A .... 'Addition'

Number in bracket refers to 'per cent level of portland cement'.

Cubes were steam-cured for 10 hours.

Composition	W/C	M	B.D.	B.L.	C.S.	C.S./B.D.
HC3 (R25)	0.967	560	1.584	3250	65	41.035
HC3 (R50)	0.911	585	1.655	5750	115	69.486
HC3 (R75)	0.889	570	1.612	4050	81	50.248
HC3 (R100)	0.867	580	1.640	3500	70	42.683
HC3 (A10)	0.767	580	1.640	5250	105	64.024
HC3 (A25)	0.591	597	1.689	7900	158	93.546
LC6 (R25)	2.070	320	0.905	550	11	12.155
LC6 (R50)	2.070	328	0.928	750	15	16.164
LC6 (R75)	2.070	336	0.950	750	15	15.789
LC6 (R100)	2.070	342	0.967	1150	23	23.785
LC6 (A10)	1.615	360	1.018	1200	24	23.576
LC6 (A25)	1.227	390	1.103	2050	41	37.171
LC6 (A40)	1.000	435	1.230	3750	75	60.976
LC6 (A55)	0.853	450	1.273	3800	76	59.701

A.4.2 Steam-curing Time Effect:

Composition HC3 (A10)

Optimal water to cement ratio 0.719 (humid weather)

0.767 (dry weather)

Steaming time (hours)	M	B.D.	B.L.	C.S.	C.S./B.D.
0	530	1.499	3200	64	42.695
	550	1.556	4000	80	51.414
5	594	1.680	6200	124	73.810
	585	1.655	6000	120	72.508
10	595	1.683	6450	129	76.649
	587	1.660	6000	120	72.289
15	595	1.683	6200	124	73.678
	595	1.683	6250	125	74.272
20	597	1.689	6200	124	73.416
	595	1.683	6200	124	73.678

A.4.3 Effect of Additives:

(a) On composition HC3 (A10):

Optimal water to cement ratio 0.719 (humid weather)

0.767 (dry weather)

Additives were added by weight per cent of total cement in the mix.

Cubes were steam-cured for 10 hours.

Additive	%	M	B.D.	B.L.	C.S.	$\frac{C.S.}{B.D.}$
None		570 567	1.612 1.604	6950 6750	139 135	86.34 83.85
$CaCl_2$	1.0	592 590	1.674 1.669	7850 7700	157 154	93.79 92.27
	2.5	622 617	1.759 1.745	10500 10550	210 211	119.39 120.92
$MgCl_2$	1.0	600 607	1.697 1.717	9500 9200	190 184	111.96 107.16
	2.5	607 602	1.717 1.703	9500 9500	190 190	110.66 111.57
$FeCl_3$	1.0	607 602	1.717 1.703	8500 8600	170 172	99.01 101.00

(b) On composition LC6:

Optimal water to cement ratio 2.0.

Additives were added by weight per cent of total cement in the mix.

Cubes were steam-cured for 10 hours.

Average cube mould edge = 7.091 cm

Additive	%	M	B.D.	Cube side (10^{-2} m)	Shrinkage (%)	B.L.	C.S.	$\frac{C.S.}{B.D.}$
None		315	0.8910	7.06	0.0345	300	6	6.734
$CaCl_2$	1.0 2.5	318 318	0.8994 0.8994	7.04 7.04	0.0515 0.0515	400 425	8 8.5	8.895 9.451
$MgCl_2$	1.0 2.5	316 320	0.8940 0.9051	7.07 7.07	0.0260 0.0260	400 300	8 6	8.949 6.629
$FeCl_3$	1.0 2.5	320 315	0.9051 0.8910	7.08 7.05	0.0175 0.043	300 300	6 6	6.629 6.734

A.4.4 Effect of Water Curing Time on Compressive Strength of Ashmoh Sand Mortar Cubes:

Ashmoh:Sand = 1:3

Water to cement ratio 0.50

Curing time (Days)	M	Cube side (10^{-2} m)	B.D.	B.L.	C.S.	$\frac{C.S.}{B.D.}$
7	718 690	7.16 7.08	1.9564 1.9442	7000 6950	140 139	71.56 71.50
14	711 740	7.10 7.185	1.9865 1.9950	8900 8850	178 177	89.61 88.72
28	720 720	7.16 7.16	1.9615 1.9615	9650 9650	193 193	98.394 98.394

A.4.5 Effect of Replacement of Ashmoh by Portland Cement on Compressive Strength of Ashmoh Sand Mortar Cubes:

Ashmoh:Sand = 1:3

Cubes were steam-cured for 10 hours.

Replacement (%)	W/C	M	B.D.	B.L.	C.S.	$\frac{C.S.}{B.D.}$
0	0.4700 Av.	760 735 747.5	2.150 2.082 2.116	10850 10500 10675	217 210 213.5	100.93 100.87 100.90
5	0.4650 Av.	725 730 727.5	2.051 2.065 2.058	10900 11250	218 225 221.5	106.29 108.96
10	0.4625 Av.	725 730 727.5	2.051 2.065 2.058	12000 11800 11900	240 236 238	117.02 114.29
100	0.4470 Av.	735 747 741	2.079 2.113	12500 13600	250 272 261	120.25 128.73

A.4.6 Upgrading of Composition LC6 by Extra Addition of Portland Cement:

Composition LC6

$CaCl_2$ 2.5% by the weight of total cement added.

Portland cement 8, 16, 25% of the weight of mix composition LC6.

Cubes were steam cured for 10 hours.

M_{WA} ... Mass of water absorbed cubes (after 24 hours in water)

Portland cement addition (%)	W/C	M	B.D.	B.L.	C.S.	$\frac{C.S.}{B.D.}$	Cube edge	Shrinkage (%)	M_{WA}	Water absorption (%)
0	2.07	312	0.883	600	12	13.59	-	-	-	-
		300	0.849	600	12	14.13	-	-	-	-
8	1.645	355	1.004	1100	22	21.91	7.07	0.0151	485	36.63
							7.06	0.0157		
							7.06	0.0157		
		365	1.0324	1150	23	22.28	7.05	0.0298	498	36.44
16	1.387	393	1.112	1600	32	28.78	7.07	0.0151	497	26.46
							7.07	0.0151		
		400	1.1314	1950	39	34.47	7.07	0.0151	501	25.25
							7.07	0.0151		
25	1.182	420	1.19	2300	46	38.66	7.07	0.0151	512	21.90
							7.06	0.0157		
		420	1.19	2550	51	42.86	7.05	0.0298	510	21.43
							7.05	0.0298		

A.4.7 Standard Samples:

Cubes were steam-cured for 10 hours.

Composition	W/C	M	B.D.	B.L.	C.S.	$\frac{C.S.}{B.D.}$	Cube edge	Shrinkage (%)	Water absorption M	Water absorption M_{WA}	Water absorption (%)
C7	0.465	720	2.0365	11500	230	112.75	7.03	0.060	715	742	3.78
		720	2.0365	10850	217	106.37	7.05	0.043	-	-	-
C8	0.49	723	2.045	11000	220	107.32	7.07	0.026	-	-	-
		727	2.056	10750	215	104.88	7.07	0.026	727	752	3.44
HC3 (A10)	0.719	570	1.612	6950	139	86.34	7.08	0.0175	-	-	-
		567	1.604	6750	135	83.85	7.08	0.0175	547	614	12.25
HC3 (A25)	0.553	610	1.725	10700	214	124.06	7.08	0.0175	-	-	-
		608	1.720	10550	211	122.32	7.09	0.009	597	645	8.04
LC6 (A40)	0.946	467	1.321	6250	125	93.99	7.05	0.043	443	540	21.89
		472	1.335	7000	140	105.26	7.06	0.0345	-	-	-

APPENDIX - 5

CONSISTENCE AND SETTING TIME OF ASHMOH AND ASHMOH-PORTLAND CEMENT MIXTURES

Room temperature 30°C

Ashmoh (%)	Portland cement (%)	Ashmoh (10^{-3} kg)	Portland cement (10^{-3} kg)	Water for consistence (cc)	Consistence W/C (%)	85% of the water for consistence (cc)	85% of consistence W/C (%)	Initial setting time (Hours)	Final setting time (Hours)
100.0	0	400	0	188	47.000	160	40.000	$2\frac{1}{4}$	6
95.2	4.8	400	20	197	46.905	167	39.762	$1\frac{1}{2}$	$5\frac{1}{2}$
90.8	9.2	400	40	201	45.682	171	38.864	1 Hour 5 min.	$5\frac{1}{4}$